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Multidimensional performance assessment for complex manufacturing environments

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Para os meus guardiões na terra: mãe, avós maternos, Sandra e Carlos

Para o meu guardião no céu, pai

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Abstract

Manufacturing companies are nowadays challenged to deal with highly competitive and constantly changing market environments, and growing demand for customized products. This leads to increased manufacturing complexity in different dimensions, including products, processes, and operations. To remain competitive, manufacturing companies must constantly design, launch and implement improvement initiatives to redirect their competitive positioning. The assessment of the effects that these initiatives will have in the future systems’ performance is critical, yet often poorly achieved.

Despite the managers’ needs for accurate tools and techniques for decision support and management of the manufacturing systems’ complexity, these tools are still unable of simultaneously assessing the impact of different parameters, e.g. related to the workforce, working policies, material and machine resources, and production capabilities, across multiple performance dimensions related to space, time, and measures detail and target. Hence, decisions depend on the experience and intuition of managers across multiple levels of decision-making. This not only is verified at the intra-firm level, but also escalates to the supply chain level.

Given the criticality of assessing the impact that the managers’ decisions will have in performance and understanding the impact of those decisions in the manufacturing systems’ behaviour, this research work intends to define a forward-looking hierarchical and hybrid performance assessment model (H2PAM) framework to support the evaluation of the effect of operational strategies on future manufacturing operations and supply chain performance. The H2PAM is directed for manufacturing companies operating in make-to-order and/or engineer-to-order strategies; commonly affected by supply chain disruptions and operating under uncertain market demand. This is achieved through the development of an approach that uses different suitable simulation models able to represent different levels of complexity, aggregation, detail, and integration in the manufacturing system, and assess the impact that different system related parameters and policies have in selected performance indicators. Considering the requirements for modelling the different parts of the manufacturing system, three modelling and simulation methods are used: System Dynamics, Discrete Event modelling and simulation, and Agent-based modelling and simulation, resulting in a hybrid approach. The models’ focus relies not only on the intra-firm level, but also includes key external influences that increase the quality of the models and extend their applicability to the supply chain level. The forward-looking H2PAM is a powerful tool for “what-if?” behavioural analysis of the internal and external manufacturing system, and to obtain insight into the manufacturing system’s complexity.

The simulation framework was applied to two case studies of companies working in make-to-order and combined make-to-order/engineer-to-order environments, producing complex, high integrity and long-life cycle products, in a low production volume. The developed models reflect the requirements of each manufacturing environment. In the first case study, an advanced manufacturing company has been considered, for which detailed models of the intra-firm operations were developed and finally extended to the supply chain level. The results obtained showed the higher uncertainty introduced by the existence of engineer-to-order projects in combined make-to-order/engineer-to-order environments, and the high impact that key performance determinants have in the performance during the execution of engineer-to-order projects.

The second case study has been that of a supplier in the aerospace industry, for which different supply chain structures have been considered, along with constraints imposed by the intra-firm manufacturing level. Analysis of the simulation models allowed understanding the key features in make-to-order and engineer-to-order manufacturing organizations.

Sumário

As empresas de manufatura são hoje desafiadas a lidar com ambientes de mercado altamente competitivos e em constante mudança, e com crescente procura por produtos customizados. Isto leva ao aumento da complexidade de fabricação em diferentes dimensões, incluindo produtos, processos e operações. Para se manterem competitivas, as empresas de manufatura devem constantemente projetar, lançar e implementar iniciativas de melhoria para redirecionar o seu posicionamento competitivo. A avaliação dos efeitos que essas iniciativas terão no desempenho futuro dos sistemas é crítica, mas muitas vezes mal alcançada.

Apesar das necessidades dos gestores de ferramentas e técnicas precisas para apoio à decisão e gestão da complexidade dos sistemas de produção, estas ferramentas são incapazes de avaliar simultaneamente o impacto de diferentes parâmetros, por exemplo relacionados com a força de trabalho, políticas de trabalho, recursos de materiais e máquinas e capacidades de produção, em várias dimensões de desempenho relacionadas com o espaço, tempo e detalhes e objetivos das medidas. Assim, as decisões dependem da experiência e intuição dos gestores que operam nos diferentes níveis de tomada de decisão. Isso não só é verificado ao nível interno da empresa, como também se intensifica para o nível da cadeia de abastecimento.

Dada a criticidade em avaliar o impacto que as decisões dos gestores terão na performance e compreender o impacto dessas decisões no comportamento dos sistemas, este trabalho de investigação pretende definir uma estrutura para um modelo preditivo, hierárquico e híbrido (H2PAM), para avaliar o efeito que estratégias operacionais terão na performance futura das operações de manufatura e da cadeia de abastecimento. O H2PAM está direcionado para empresas que operam em produção despoletada por encomenda/conceção despoletada por encomenda[1], comumente afetadas por disrupções na cadeia de abastecimento e que operam com grande incerteza na procura de mercado. Isto é concretizado pelo desenvolvimento de uma abordagem que usa diferentes modelos de simulação capazes de representar diferentes níveis de complexidade, agregação, detalhe, e integração no sistema de manufatura, e avaliar o impacto que diferentes parâmetros e políticas do sistema têm em indicadores de performance selecionados. Considerando os requisitos de modelação para as diferentes partes do sistema de manufatura, são utilizados três métodos de modelação e simulação: dinâmica de sistemas (System Dynamics), modelação e simulação por eventos discretos, e modelação e simulação baseada em agentes, resultando numa abordagem híbrida. O foco dos modelos não está só no nível interno da empresa, mas também inclui influências externas importantes, que aumentam a qualidade dos modelos e alargam a sua aplicabilidade ao nível da cadeia de abastecimento. O H2PAM preditivo é uma poderosa ferramenta para análises comportamentais do sistema de manufatura “e se?”, aos níveis interno e externo, que permite obter informações sobre a complexidade do sistema de manufatura.

A estrutura da simulação foi aplicada a dois casos de estudo de empresas que trabalham em ambientes de produção por encomenda e em ambientes combinados de produção/conceção despoletadas por encomenda, produzindo produtos complexos, de alta integridade e longos ciclos de vida, em baixo volume de produção. Os modelos desenvolvidos refletem os requisitos de cada ambiente de manufatura. No primeiro caso de estudo foi considerada uma empresa de manufatura avançada, para a qual foram desenvolvidos modelos detalhados das operações ao nível interno da empresa, que foram depois alargados para o nível da cadeia de abastecimento. Os resultados obtidos mostram a maior incerteza existente quando existem projetos em conceção despoletada por encomenda em ambientes combinados de produção/conceção despoletadas por encomenda, e o grande impacto que determinantes chave da

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[1] Produção despoletada por encomenda corresponde ao termo em inglês *make-to-order* e conceção despoletada por encomenda corresponde ao termo em inglês *engineer-to-order*

performance têm na performance durante a execução dos projetos em conceção despoletada por encomenda.

O segundo caso de estudo foi o de um fornecedor na cadeia de abastecimento da indústria aeroespacial, para a qual diferentes estruturas da cadeia de abastecimento foram consideradas, em conjunto com as restrições impostas ao nível da produção interna da empresa. A análise dos modelos de simulação permitiu compreender as principais características das organizações de manufatura que operam em produção por encomenda e desenho por encomenda.

List of Publications

In the context of this work, different papers have been prepared and submitted/published. The main publications have been submitted/published in international journals and conferences. The papers are listed below. Some of the papers have not yet been submitted and are currently under their final preparation steps for the submission process. Conference papers are papers A and F. Papers B and D have been presented at international conferences and published as a journal special issue. Papers C, E, and G have been submitted/published in international journals.

The additional publications have been submitted as part of this thesis, but represent highly preliminary work, or work that has been part of major collaboration with other researchers. Though not included in the extended abstracts in the main body text of the thesis, whenever possible, these are included in the appendices. Additional publications are conference publications: two international and one national conferences. Table 1 summarizes the papers that have been prepared/published, their classification, and status.

Table 1. Publications which are part of the research work

Paper	Type	Comments	Status	Journal/conference name
A	Conference paper	-	Published	IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)
B	Conference paper	Published as a journal special issue	Published	Procedia Manufacturing
C	Journal paper	-	Published	International Journal of Production Research
D	Conference paper	Published as a journal special issue	Published	Procedia Manufacturing
E	Journal paper	-	Published	International Journal of Production Research
F	Conference paper	Presentation at a forum, without publication	N/A	5th International EurOMA Sustainable Operations and Supply Chains Forum
G	Journal paper	Submitted to the Journal of Cleaner Production	First review	-
A1	Conference paper	-	Published	2015 International Conference on Industrial Engineering and Systems Management (IESM)
A2	Conference paper	Presentation at a conference, without publication	N/A	23rd EurOMA Conference
A3	Conference paper	-	Accepted	XIX Congresso da Associação Portuguesa de Investigação Operacional (IO 2018)

Main publications

Paper A: Barbosa, C., & Azevedo, A. (2015, 6-9 Dec. 2015). Evaluation of improvement actions impact on manufacturing operational performance. Paper presented at the 2015 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM).

Author contribution to paper A

The paper results from a joint effort with Professor Américo Azevedo, the thesis supervisor. The topic of the paper has been proposed by Professor Américo Azevedo, while the literature has been revised, and the paper has been structured and written by Cátia Barbosa. The final paper has been revised by Professor Américo Azevedo.

Paper B: Barbosa, C., & Azevedo, A. (2017). Hybrid Simulation for Complex Manufacturing Value-chain Environments. Procedia Manufacturing, 11 (Supplement C), 1404-1412. doi: https://doi.org/10.1016/j.promfg.2017.07.270

Author contribution to paper B

The paper results from a joint effort with Professor Américo Azevedo, the thesis supervisor. The idea for the paper has been a joint effort between the authors. Cátia Barbosa revised the literature, organized the data and structured and wrote the paper. The final paper has been revised by Professor Américo Azevedo.

Paper C: **Barbosa, C.**, & Azevedo, A. (2018). Hybrid modelling of MTO/ETO manufacturing environments for performance assessment. International Journal of Production Research, 56(15), 1-25. doi:10.1080/00207543.2017.1421788

Author contribution to paper C

The paper results from a joint effort with Professor Américo Azevedo, the thesis supervisor. The idea for the model presented in the paper, and the paper writing have been undertaken by Cátia Barbosa. Professor Américo Azevedo suggested alterations to the paper before initial submission and helped prepare the response to the reviewers' comments after the first-round review.

Paper D: Barbosa, C., & Azevedo, A. (2018). Towards a hybrid multi-dimensional simulation approach for performance assessment of MTO and ETO manufacturing environments. Procedia Manufacturing, 17 (Suplement C), 852-859. doi: https://doi.org/10.1016/j.promfg.2018.10.137

Author contribution to paper D

The paper results from a joint effort with Professor Américo Azevedo, the thesis supervisor. The idea for the model presented in the paper, and the paper writing have been undertaken by Cátia Barbosa. Professor Américo Azevedo revised the final paper.

Paper E: Barbosa, C., & Azevedo, A. (2018). Assessing the impact of performance determinants in complex MTO/ETO supply chains through an extended hybrid modelling approach. International Journal of Production Research, 1-21. doi:10.1080/00207543.2018.1543970

Author contribution to paper E

The paper results from a joint effort with Professor Américo Azevedo, the thesis supervisor. The idea for the model presented in the paper, and the paper writing have been undertaken by Cátia Barbosa. Professor Américo Azevedo suggested alterations to the paper before initial submission.

Paper F: Barbosa, C., Azevedo, A., Malarranha, C., Carvalho, A., & Barbosa-Póvoa, A. (2018). Towards a supply chain sustainability conceptual model for performance assessment: a case in the commercial aircraft industry. Paper presented at the 5th International EurOMA Sustainable Operations and Supply Chains Forum, Kassel, Germany.

Author contribution to paper F

The paper results from a joint effort between researchers in the Introduction of Advanced Materials Technologies into New Product Development for the Mobility Industries (IAMAT) project, and for this the topic of the paper is originated by the challenges proposed in the context of this project. The idea for the model has been conjointly developed by Cátia Barbosa and Carlos Malarranha. The selection of the performance indicators, the model development and results analysis have been undertaken by Cátia Barbosa. The literature review for the paper and the model input data assessment have been made by Cátia Barbosa and Carlos Malarranha. The paper has been revised prior to submission by Professors Ana Barbosa-Póvoa, Ana Carvalho, and Américo Azevedo.

Paper G: Barbosa, C., Azevedo, A., Malarranha, C., Carvalho, A., & Barbosa-Póvoa, A. Sustainability performance assessment in the commercial aircraft MTO supply chains: a hybrid simulation approach applied to the real case of an aerospace manufacturer. *Paper submitted to the Journal of Cleaner Production.*.

Author contribution to paper G

Paper G is an extended version of paper F. For this, the role of the involved researchers remained the same.

Additional papers

A1. Barbosa, C., & Azevedo, A. (2015, 21-23 Oct.). Operations strategy frameworks in manufacturing, services and product-service systems. Paper presented at the 2015 International Conference on Industrial Engineering and Systems Management (IESM).

Author contribution to the paper A1

The paper results from a joint effort with Professor Américo Azevedo, the thesis supervisor. The topic of the paper has been proposed by Professor Américo Azevedo, while the literature has been revised, and the paper has been structured and written by Cátia Barbosa. The final paper has been revised by Professor Américo Azevedo.

A2. Barbosa, C., & Azevedo, A. (2016). Towards a System Dynamics approach for performance evaluation of assembly production areas. Paper presented at the 23rd EurOMA Conference, Trondheim, Norway.

Author contribution to the paper A2

The paper results from a joint effort with Professor Américo Azevedo, the thesis supervisor. The topic of the paper has been proposed by Professor Américo Azevedo, while the model has been developed, and the paper has been structured and written by Cátia Barbosa. The final paper has been revised by Professor Américo Azevedo.

A3. Barbosa, C., Cunha, N. F. E., Malarranha, C., Pinto, T., Carvalho, A., Amorim, P., Carvalho, M. S., Azevedo, A., Relvas, S., Pinto-Varela, T., Barros, A. C., Alvelos, F., Alves, C., Sousa, J. P. D., Almada-Lobo, B., Carvalho, J. V. D. & Barbosa-Póvoa, A. (2018, 5-7 Sept.). Towards an Integrated Framework for Aerospace Supply Chain Sustainability. *XIX Congresso da Associação Portuguesa de Investigação Operacional (IO 2018).* Aveiro.

Author contribution to the paper A3

The paper results from a joint effort between researchers in the IAMAT project, and for this the topic of the paper is originated from the challenges proposed in the context of this project. Cátia Barbosa was fully responsible for sub-section 3.3, and jointly organized and wrote sections 1, 2, and 4 with Nuno Cunha, Carlos Malarranha, and Telmo Pinto. The other researchers in the paper have been responsible for the paper revision.

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List of Abbreviations and Acronyms

Agent Based Simulation (ABS)

Analytic Hierarchy Process (AHP)

Analytic Network Process (ANP)

Assemble-to-Order (ATO)

Balanced Scorecard (BSC)

Bill of Materials (BOM)

Business-to-Business (B2B)

Competitive Priorities (CPs)

Critical Path Method (CPM)

Customer Order Decoupling Point (CODP)

Data Envelopment Analysis (DEA)

Discrete Event Simulation (DES)

Decision Making Units (DMUs)

Design-of-Experiments (DOE)

Earliest Due Date (EDF)

Engineer-to-Order (ETO)

Enterprise Resource Planning (ERP)

First In First Out (FIFO)

Genetic Algorithms (GA)

Hierarchical and Hybrid Performance Assessment Model (H2PAM)

IAMAT (Introduction of Advanced Materials Technologies into New Product Development for the Mobility Industries)

Make-to-Order (MTO)

Make-to-Stock (MTS)

Manufacturing Resources Planning (MRP II)

Material Requirements Planning (MRP)

Multi-Criteria Decision Analysis (MCDA)

Multiple Criteria Decision Making (MCDM)

Neural Networks (NN)

Operations Research (OR)

Original Equipment Manufacturer (OEM)

Performance Determinants and Capabilities (PDC)

Plan-Do-Check-Act (PDCA)

Performance Measurement (PM)

Performance Measurement Systems (PMSs)

Priority Based -EDF (PB-EDF)

Program Evaluation and Review Technique (PERT)

Return on Investment (ROI)

Shortest Processing Time First (SPTF)

System Dynamics (SD)

Triple Bottom Line (TBL)

Unified Modelling Language (UML)

Vacuum Assisted Resin Injection (VARI)

Vacuum Bag Only (VBO)

Work-Centres (WCs)

Work-In-Process (WIP)

Table of contents

Chapter 1 – Introduction, research objectives and research questions

Throughout this chapter, the research topic of performance assessment in complex manufacturing environments is introduced. The chapter starts with a description of the critical challenges for modern and complex manufacturing environments and the criticality that performance assessment assumes today for these systems. It also briefly introduces current performance assessment systems' limitations. Finally, the research objectives and research questions are formulated upon the collected information.

1.1. Modern manufacturing systems – the criticality of performance assessment

Nowadays, manufacturing organizations are operating under highly uncertain and unpredictable circumstances (ElMaraghy et al., 2012). The globalization and interconnectedness of markets, demand fluctuations, and customer requirements for products with high quality (Efthymiou et al., 2014), reliability (Tiwari et al., 2010), low prices, obtained with a short lead time and with high levels of customization, have been increasing the manufacturing complexity (Efthymiou et al., 2014). Increased complexity resulting from higher uncertainty in operations is undoubtedly a major challenge for manufacturing systems (ElMaraghy et al., 2012), leading to the manufacturing strategy assuming critical relevance to managers (Kim and Arnold, 1996). In this context, the manufacturers' performance and survival rely on the management of change, the coordination and control of the manufacturing complexity (Vrabic and Butala, 2012), and the implementation/reorganization of initiatives to achieve improvements in the design and manufacturing processes (Tiwari et al., 2010, Gomes et al., 2004). This means that only through a proper implementation of the manufacturing strategy, companies will remain competitive and capable of satisfying customers efficiently and effectively.

Nearly 20 years ago, Tahmassebi (1999) referred that the business growth required a proper understanding and control of the manufacturing complexity. However, understanding complexity involves managing a large volume and variety of information (EIMaraghy and Urbanic, 2003). Adding to this, the very definition of manufacturing complexity remains to be clarified. As Fredendall and Gabriel (2003) referred, defining manufacturing complexity is not an easy task. Magee and de Weck (2004) presented the following definition of a complex system: *"... a system with numerous components and interconnections, interactions or interdependencies that are difficult to describe, understand, predict, manage, design, and/or change."*. Manufacturing systems can, for this, be described as complex. First, dynamic manufacturing systems consist of many elements that may have (or not) obvious relationships among them, and these relationships are often not simple, nor completely organized (Fredendall and Gabriel, 2003). Second, manufacturing systems can entail a large number of interacting machines, tools, computers, human operators, and managers. These elements interact with each other and with the surrounding environment (ElMaraghy et al., 2012). Third, the products' complexity has a direct influence in the process complexity, with complexity increasing as the number and diversity of features to be manufactured, assembled and tested, and the number, type, and effort of tasks increase (EIMaraghy and Urbanic, 2003). Finally, in manufacturing systems, is difficult to predict the effect that a decision will have on the system performance (Kuzgunkaya and ElMaraghy, 2006).

Complexity in manufacturing systems has been regarded as a three-dimensional feature: product, process, and operations. At the product level, complexity is associated with the type of materials used, the product design, the components and the specifications. At the process level, complexity results from the manufactured products, the volume requirements, and the work environment, including the tools used, and the type of equipment. The operational complexity results from the product, process, and production logistics complexity (EIMaraghy and Urbanic, 2003, EImaraghy and Urbanic, 2004), and the temporal aspects of the coordination and control of the manufacturing systems (Vrabic and Butala, 2012). Higher levels of complexity are generally experienced by manufacturing environments with lower production volume. This is a consequence of the unique jobs that must be handled and the more complex interactions that exist between different areas of the manufacturing plant (Bozarth et al., 2009). As customers are increasingly giving importance to customized products, often one-of-a-kind, the relevance of the Engineer-to-Order (ETO) companies across many industries has boosted (Adrodegari et al., 2015). As ETO manufacturers, that often earn most of their revenues from Make-to-Order (MTO) products (Willner et al., 2014), are low volume manufacturers, understanding their complexity and investing in tools that allow envisioning their future performance and assessing the impact of improvement initiatives in their operations becomes critical.

Clearly understanding manufacturing complexity will allow these systems to become more productive and predictive (Efthymiou et al., 2012). One should bear in mind that manufacturing complexity should be studied from the perspective that it results from the interactions between social and technical systems (Zhang, 2011). An effective and efficient system can only exist if there is a proper balancing between the human features, needs, skills and capabilities, and the technical and business environments (EImaraghy and Urbanic, 2004). The resources owned by a company determine the ability to achieve a certain competitive positioning; hence, the operations decisions that affect the system resources will have a direct impact on the firm performance and can influence the future strategy of the company (Iansiti and Serels, 2013).

In complex manufacturing environments, it is very difficult to predict the near-future performance, or accurately determining how a certain level of performance has been achieved. Often managers are challenged by the uncertainty in predicting the impact that today’s decisions will have in the future manufacturing system’s performance (Zhang, 2011). Mostly, today’s decisions are based on the manager’s past experience, and often reflect the subjectivity of the information that is transmitted inside the company, and the reduced understanding about the real complexity of manufacturing systems (Vrabic and Butala, 2011). Manufacturing organizations are now increasingly interested in developing decision support tools that will allow managers to quantitatively assess the impact of their decisions in the future operational performance. This is enhanced by the fact that implementing improvement initiatives is very challenging, given the diverse nature of the manufacturing activities and functions that make the starting point to implement improvement initiatives a controversial issue (Aqlan and Al-Fandi, 2018). Despite Neely et al. (1995) identified the topic of predictive performance as one of the most promising in Performance Measurement Systems (PMSs), it still is poorly understood (Busi and Bititci, 2006), with a scarce number of works focusing on integrating a forward-looking perspective into the PMSs.

A proper understanding of the drivers of performance is key for an effective management of operations and development of operations strategy (Silvestro, 2014). Aiding managers in the decision making process must consider predicting the impact that the manufacturing/operational strategy adopted will have on performance (Unahabhokha et al., 2007). The operations strategy (or manufacturing strategy) allows a firm to convert a set of objectives into action plans, by following a choice pattern to perform decisions which are medium to long term (Lowson, 2001, Slack and Lewis, 2011, Reid and Sanders, 2011). It is, therefore, relevant developing an approach that not only aids in identifying opportunities for improvement in the manufacturing systems, but that also quantitatively and predictively assesses the impact that improvement action plans will have in performance.

By considering the above and that manufacturing performance is one of the main determinants of competitiveness for companies (Leachman et al., 2005), the aim of this research work will focus on providing an integrative frame that will allow managers to understand the impact that certain operational decisions will have in the future manufacturing systems performance, with a specific focus on industries providing highly customized products to the end customers.

1.2. Research objectives and research questions

In this research work, we intend to define a framework to support the assessment of the effect of operational initiatives on the future multidimensional operational performance of complex manufacturing environments. Additionally, it is the purpose of this work exploring how to model these complex manufacturing systems, focusing on the resources and process dimensions, and including key value chain variables in the models. Manufacturing systems are herein seen as a whole, and follow the definition of manufacturing as in the CIRP Encyclopedia of Production Engineering (Segreto and Teti, 2016): *"... all functions and activities directly contributing to the making of goods."*. This definition extends the meaning of a manufacturing system beyond production, by including other value adding activities, as the product development, assembly, and organizational functions as production planning and control. Despite this definition of a manufacturing system, from the value chain activities point of view, the manufacturing function is herein seen from the classical production perspective.

Given the relevance of MTO and ETO environments in the contemporary manufacturing scenario, these environments are the focus of this research work. The proposed framework includes a methodology and a set of suitable models able to represent the different levels of complexity of the manufacturing system and gain insight into its structure. To achieve this, there is the need to explore how to model complex manufacturing systems, how to include key external influences to increase the quality of the models and develop the functional elements to be included in a predictive Performance Measurement (PM) framework to support the decision-making process related to the operational performance.

Two research questions were formulated to guide the review and analysis of the literature, and the manufacturing system modelling process, considering the above-mentioned research objectives.

RQ1: How can companies quantitatively predict the impact of key performance determinants on the MTO/ETO manufacturing environments future operational performance?

Due to the complexity that is experienced in modern manufacturing environments, especially in MTO and ETO, it becomes key investing in tools that allow an accurate assessment of performance and the prediction of the effect that today's decisions will have in the future of the manufacturing system, across multiple dimensions. If the performance is appropriately estimated, it is possible to obtain, with some degree of confidence, a perspective about the future of the manufacturing systems. However, this is not straightforward. On one hand, there is the need to quantify the results of the decisions made and, on the other hand, there is the need to understand which are the key manufacturing system variables that have an impact on performance.

Considering the above, this research question has two objectives. The first objective encompasses an assessment of the quantitative operations research techniques which can have a role in the predictive performance assessment domain, and that allow modelling the (static and dynamic) complexity of manufacturing systems. This analysis is framed by the needs that exist for the PM domain and the constraints and particularities of the MTO and ETO value chains. The second objective includes the analysis of the literature to discover the key performance determinants (elements that have an impact on the performance of the systems) of the MTO/ETO environments; and to understand which key system variables are affected by those determinants. The important quantitative performance indicators dispersed across multiple dimensions, and that have a great impact on the competitiveness of the MTO/ETO manufacturing environments, are also explored.

RQ2: How to model and gain insight into complex MTO/ETO manufacturing environments? Which key processes should be included in the modelling exercise?

The focus of this research question is the study of the MTO/ETO manufacturing environments. The purpose is to gain insight into the main stages and activities that exist in these value chains. By unveiling the key activities and the contents of those activities, the complexity of these value chains can be better understood. This means that by structuring the system in this way, the key activities that have an impact on the performance of these systems can be discovered, and a better insight about the complex structure of these value chains can be achieved.

Summarizing, it is the purpose of this research question to segment the MTO/ETO value chains (internal and external) to gain insight about these systems and provide a relevant input to the development of models of these systems. The input for the modelling exercise is given by the decomposition of the system, that contains the key activities that determine the performance. It should be explored how these activities can be appropriately represented in the manufacturing system models.

1.3. Expected outcomes

The most important contribution of this research work is in the manufacturing performance assessment area, with a focus on complex MTO and ETO manufacturing environments. To attain a significant contribution for companies operating in complex MTO/ETO environments, an innovative framework to support the assessment of the effect of operational initiatives on the future multidimensional operational performance is proposed. A predictive/forward-looking approach is especially significant given the identified research gaps. Considering this predictive perspective, the use of different modelling methods is proposed. This allows capturing unique features of the manufacturing systems' complexity, enhancing the understanding of the systems and aiding in the decision-making process, through the envisioning of the future performance. Two main outcomes have been established for this research work:

O1. Multidimensional performance assessment framework: Considering a predictive performance capability, the first outcome of this work is a performance assessment framework that targets different functions of the manufacturing system. The modelling of the system consists in the starting point of the framework. By modelling the complexity of the manufacturing system, the critical performance drivers can be discovered, while the most important sources of complexity can be identified. The use of different modelling methods allows targeting varied levels of detail for the manufacturing system functions. This will allow including in the manufacturing system models, details related to the internal firm's environment, as well as including key external influences that can affect multiple dimensions of the manufacturing system's performance. The Hierarchical and Hybrid Performance Assessment Model (H2PAM) – hierarchical due to the different levels of detail considered for different manufacturing functions, and hybrid given the use of different modelling and simulation methods – is the framework proposed for the predictive performance assessment. In the context of this work, a framework is a methodology used for assisting the decision-making process in the MTO/ETO manufacturing environments.

O2. Roadmap for complex manufacturing systems' modelling and simulation methods selection: Given the different levels of detail and the need to model functions which are very different in nature, within the same manufacturing environment, it becomes appropriate to establish a roadmap for the selection of the appropriate modelling methods. The roadmap is a guiding tool that supports the framework design for the research outcome number one. Through the combination of different modelling methods enhanced flexibility and the possibility of modelling enterprise-wide solutions are achieved. This allows tackling the problem of *ad hoc* approaches to the development of hybrid models (Glazner, 2009).

1.4. Thesis outline

The document of this dissertation is organized in five main chapters and a set of appendices that represent the papers that have been published/submitted in the context of this work.

After presenting the introduction, research objectives and research questions in the first chapter, chapter 2 of this thesis is dedicated to exploring the conceptual framework of this work. It starts with an investigation of key concepts in the manufacturing complexity domain, with a focus on low volume and high variety manufacturing environments. Following, there is a review of the manufacturing performance measurement literature, performance measurement frameworks, models for performance assessment and performance indicators. This discussion leads to the justification of the use of a simulation approach as the research method and deriving the key performance indicators in the MTO/ETO domain. Also, in chapter 2, the performance determinants for MTO and ETO environments are retrieved from the literature and the general framework for the development of models for performance assessment is explored.

Chapter 3 focuses on the research methodology and the research design. The use of simulation as a scientific method, its strengths and weaknesses are discussed, alongside exploring the use of hybrid simulation approaches and establishing a roadmap for the selection of simulation methods for the different manufacturing functions in the MTO/ETO value chain. The case studies used for the application of the models are also presented in this chapter. In chapter 4, the papers that have been developed, published or submitted to international journals and scientific conferences are introduced. An extended summary of the papers and their relation to the thesis are presented.

The thesis concludes in chapter 5, with the conclusions and future research directions, the benefits, the improvement opportunities and the potential as a decision support and insight gaining tool of the proposed approach.

The thesis outline has been established in line with the papers that have been published/submitted for publication. Notwithstanding this, partially repeated information may appear, specifically between chapters 2 and the appendices, and between chapters 3 and the appendices. This was deemed appropriate to improve the information flow, provide relevant information where needed, and help the reader understand the key concepts included in the thesis before reading the full papers' contents presented in the appendices. The contents in chapters 2 and 3 partially rely on information contained in the introductions and literature reviews of the papers in the appendices. Figure 1.1 shows where chapters 2 and 3 capture information from the papers in the appendices.

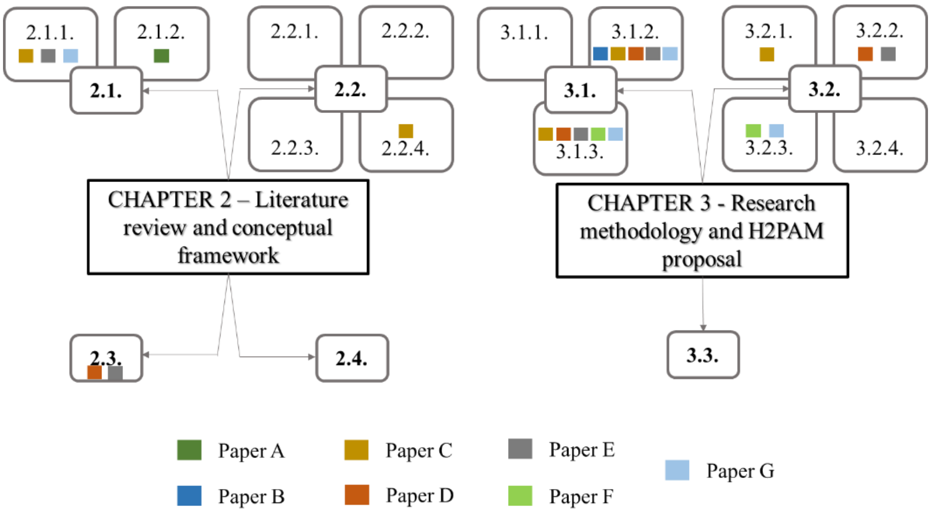


Figure 1.1. Information captured simultaneously by chapters 2 and 3 and the appendices.

Chapter 2 – Literature review and conceptual framework

This chapter's objective is introducing the theoretical background of the research developed in this thesis. It includes a context setting sub-section, in which the MTO and ETO environments features are explored. Addressing the research questions introduced in chapter 1, an overview of previous research on PM is presented, followed by the critical performance determinants in MTO and ETO. The chapter ends with the proposed conceptual thesis framework.

2.1. Complexity in the manufacturing supply chain – the MTO and ETO cases

Dynamic manufacturing systems and their supply chains are fundamentally complex. On one hand, the supply chain complexity results from the number of echelons in the supply chain, and the number of facilities in each echelon (Beamon, 1999); on the other hand, the dynamism and integration of manufacturing systems drive a high number of decisions that have to be made, whose impact in the future performance is hardly predictable (Deshmukh et al., 1998). In fact, the manufacturing environments characterized by low volume production are generally subject to higher levels of complexity (Bozarth et al., 2009), which enhances the relevance of studying the MTO and the ETO manufacturing. In this sub-section the features of the MTO and ETO environments are explored, followed by the complexity subject in low volume manufacturing environments. Throughout this work, the terms supply chain and value chain are interchangeably used.

2.1.1. MTO and ETO manufacturing

Manufacturing companies are usually classified along a continuum of strategies, including Make-to-Stock (MTS), Assemble-to-Order (ATO), MTO, and ETO (Rahim and Baksh, 2003, van Donk and van Doorne, 2016). These strategies are associated to the Customer Order Decoupling Point (CODP) that corresponds to the point that separates decisions made under certainty from those that are made under uncertainty in what concerns to the customer demand (Rudberg and Wikner, 2004). It is seen as a stock holding point (Gosling and Naim, 2009) that allows classifying the amount of value-adding activities that are developed considering the customer demand information (Rudberg and Wikner, 2004). In other words, it splits the part of the supply chain that uses forecast planning, from the part of the supply chain that responds directly to the customer (Gosling and Naim, 2009, Gosling et al., 2013), and acts as a strategic buffer against variability in demand (Gosling and Naim, 2009, Olhager, 2010). Delivery promises, lead time estimation, and capacity availability are estimated based on the stock availability at this point (Olhager, 2010). Upstream from the CODP, products are produced to forecast, and downstream products are pulled by the customer (Gosling and Naim, 2009). The further downstream the location of the CODP, the higher the number of activities that must be executed under uncertainty, and the further upstream the CODP, the higher the number of activities that are based on the order commitment and certain information (Rudberg and Wikner, 2004).

The selected manufacturing/supply chain strategy must match the demand features of a product, product family, or market (Hilletofth, 2009). In MTS manufacturing there is a high volume production of standard products with a narrow range (Olhager, 2012), and the target market is the end customer. Inventories are usually kept high to avoid shortage (Rahim and Baksh, 2003). The end customer has no direct input into the configuration of the product, which is usually purchased from retailers. Profit margins are low, and the demand for these products is usually stable and can be forecasted with low error. Production processes associated with MTS manufacturing are highly automated continuous processes or high volume assembly lines (Stavrulaki and Davis, 2010). In ATO production, the products offered to the customers, despite presenting a small degree of customization, are produced with common and standard components, which are kept in stock for the anticipation of future orders, and that can be assembled in different options. Upon order receipt, there is the assembly of the finished product to meet the customer requirements (Amaro et al., 1999). Products manufactured following an ATO strategy are higher priced products that have a high obsolescence rate. Forecasting occurs at the component level. The amount of time a customer must wait to obtain the products is higher than in the MTS case, as the assembly operations occur after an order is received. The production processes often use modular approaches, with standard components being produced in appropriate batch sizes and finally assembled as per customer orders (Stavrulaki and Davis, 2010). In MTO manufacturing, products are sophisticated and have long lead times, are produced in small lot sizes and have high levels of customization. Despite this, the customer still must choose among a set of available alternatives (Willner et al., 2014). The MTO strategy should be selected for special products with a wide range and low individual product volume per period (Olhager, 2012). In ETO, the CODP is located at the design stage (Gosling and Naim, 2009), and highly customized products are designed and engineered according to the specifications established by the customer (Pandit and Zhu, 2007, Lu et al., 2009). In ETO, the degree of customization can vary from a small extension of a product parameter to the design of a completely new product (Willner et al., 2014). ETO companies operate under low production volumes per product type and with a high degree of customization (Lu et al., 2009). Most produced products are capital equipment goods in industries as the industrial machinery, plant equipment, power generators, construction, shipbuilding, and aerospace (Gosling et al., 2013, Rahim and Baksh, 2003, Hendry, 2010). These are usually big, complex (Rahim and Baksh, 2003, Lu et al., 2009), very expensive when compared to mass customized or mass produced products (Lu et al., 2009), and meant for industrial customers, to be used in downstream operations (Rahim and Baksh, 2003). Based on the works by Olhager (2012) and Willner et al. (2014), Figure 2. 1 shows the different CODP alongside the manufacturing/supply chain strategies.

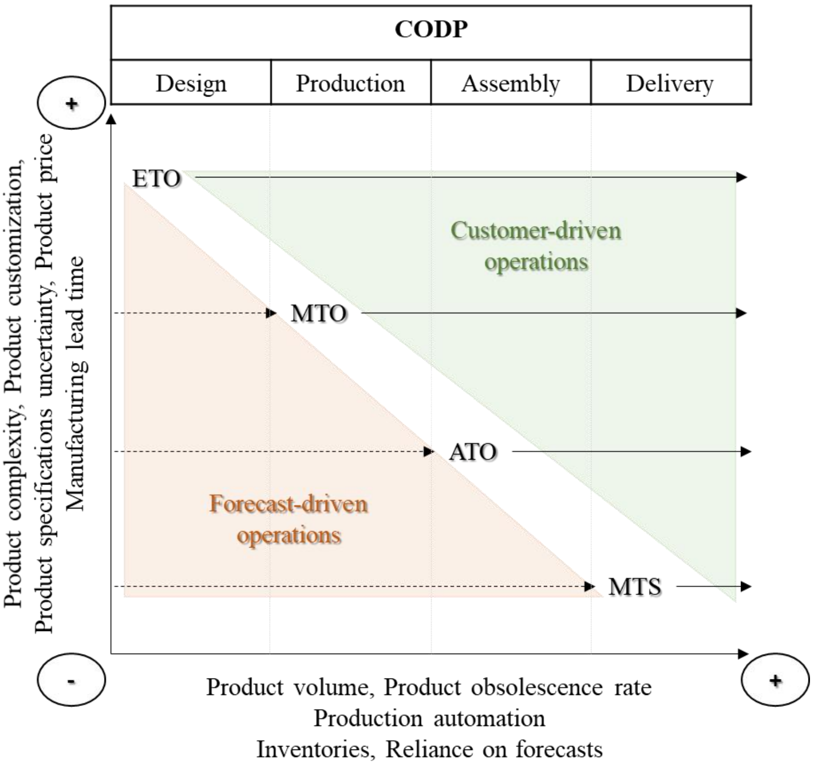


Figure 2. 1. The different CODP and the manufacturing/supply chain strategies (based on (Olhager, 2012, Willner et al., 2014)).

The MTO and ETO manufacturing supply chains are highly intertwined. Most of the ETO manufacturers do not exclusively engage in producing goods that require customer specific engineering changes. These earn most of their revenues from MTO products (Willner et al., 2014). Some literature, as Olhager (2012) and van Donk and van Doorne (2016) refer to the MTO material flow as including the MTO and ETO perspectives, arguing that the supply chains are identical from this perspective. Also Stavrulaki and Davis (2010) refer that the ETO supply chain is similar to the MTO, however it allows customers to design the products to meet their unique individual tastes. The literature still struggles to settle on a definition of these manufacturing strategies. As noted by Gosling and Naim (2009) there are variations in the definition of ETO, in what concerns to the extension of the design dimension. While some authors argue that completely new designs are developed to order, others agree that ETO companies also modify existing designs to accommodate new customer requirements. It is in the design process that the main differences between MTO and ETO exist. In MTO, the design process is mostly linear, while in ETO, it is prone to countless iterations and loops that result from interactions with the customer (Willner et al., 2014). Given this, we adopt the following definitions for MTO and ETO manufacturing:

MTO manufacturing: The operations needed to produce a product start after the receipt of a customer order. Some customization is allowed considering limited available design options.

ETO manufacturing: The products to be produced are designed considering the customer specifications, or a significant customization is undergone. The products are unique and result in a different number of parts, Bill of Materials (BOM), and shop floor routings.

From the demand perspective, the major challenge for MTO and ETO manufacturers is predicting customer requirements and specifications (Babu, 1999, Hicks and Braiden, 2000, Mello et al., 2015). Markets are difficult to forecast as the future orders' volume and products' specifications are unknown (McGovern et al., 1999). It is not unusual that a new product has to be designed for each new customer order. Products are typically produced once, and design and manufacturing processes, as well as the sequence of operations, are likely to vary from one product to another. Order repeat is possible for some products, and the same design and manufacturing processes can be used (Rahim and Baksh, 2003). There is irregular and discontinuous demand at the product (end item) level, dependent demand relationships among items, and lumpy and deterministic demand at the component level (Sahin and Jr., 2005). Components can be required in different volumes, have different degrees of customization (some are standard components, while others are highly customized), and have different technological requirements (Hicks and Braiden, 2000, Hicks et al., 2000). As this violates all the assumptions of statistical inventory control models (Sahin and Jr., 2005), it becomes impossible keeping inventories (Babu, 1999), and the relevance of the planning functions and contract negotiation is enhanced (McGovern et al., 1999). Tailored management approaches are needed to handle all the processes, from the design and engineering, to the production and delivery (Adrodegari et al., 2015), as delays are a major problem in these environments and impact the performance of companies and their supply chains (Mello et al., 2015).

In ETO environments, there is an extensive interaction with the customer, who presents the products' technical requirements and is involved in the design process and approval (Lu et al., 2009). As the design can be exclusively for a particular customer, the design frequency is high (Rahim and Baksh, 2003), and data is often unavailable (Alfieri et al., 2012). The customers of these companies are exposed to the entire product lead time, including the conceptual and detailed design, procurement, manufacturing, assembly, testing, and commissioning (McGovern et al., 1999, Pandit and Zhu, 2007). The product development can be extremely time consuming, as there are many tasks that must be performed; it is considered the time bottleneck in the value chain processes (Amrani et al., 2010), with a high impact in the delivery lead time (Mello et al., 2015, Gosling and Naim, 2009). It may take up to one-half of the total lead time (Grabenstetter and Usher, 2015). As previously mentioned, in MTO, part of the product can be built to the customer's specifications, but the customer does not have direct input into the overall product design that remains fixed within the design parameters established by the manufacturing company. In MTO, customization consists in a combination of standardized modular components and additional elements that are specifically produced to meet individual customer requirements (Stavrulaki and Davis, 2010).

Orders in ETO can be managed as projects (Gosling and Naim, 2009), given their uniqueness and temporariness. During the project execution, manufacturing is just a part of the project (Yang, 2013) and the design stage is the core process that is never outsourced (Grabenstetter and Usher, 2015). In the same ETO environment, several projects with different completion levels and subject to frequent changes co-exist (Adrodegari et al., 2015). Processing times and routings in the shop floor are highly uncertain, which difficult the prediction of the work distribution among the different machines (Babu, 1999).

Following the product-process matrix proposed by Hayes and Wheelwright (1979), at the manufacturing level, MTO and ETO environments are characterized by a functional layout of the equipment and a high flexibility to allow the production of a wide range of products (Babu, 1999). The Job shop production gives the ultimate form of high variety manufacturing, with different orders following different routings along multi-purpose machines (Beemsterboer et al., 2017), and is the process type used in low volume and high variety products (Stavrulaki and Davis, 2010, Hendry, 2010). Planning in MTO and ETO is very challenging. For this contribute the inability to store large amounts of inventory, the high number of products that can be produced, and the production limitations, including the number of employees, the capacities of the resources, the storage space for the Work-In-Process (WIP) or finished product inventory, the week work hours and product demand (Neureuther, 2004). Companies that produce many low volume and customized products are expected to follow a chase planning strategy (Olhager, 2010). By choosing this planning strategy, companies produce only the needed to satisfy demand in a given period, which leads to production rates varying with the demand fluctuation. Also, it allows minimizing the finished goods holding costs. On the downside, this planning strategy requires constantly changing the capacity needs and holding enough equipment to satisfy peak demand (Reid and Sanders, 2011). For planning purposes, ETO and MTO manufacturers use Material Requirements Planning (MRP) (Olhager, 2010) and/or Enterprise Resource Planning (ERP) (Grabenstetter and Usher, 2015) systems. MRP planning systems use a backward scheduling approach (Slack et al., 2010), which means that for scheduling purposes, it starts by scheduling the job’s last activity so that it finishes on the due date. From that, it works backwards for the remaining activities, including the ordering of needed materials (Reid and Sanders, 2011).

Outsourcing is an alternative used by the ETO manufacturers for cost and lead time reduction (Hicks et al., 2000, Hicks et al., 2001). For this, outsourcing decisions and the relationships with the supplying partners have to be carefully managed. From an inventory perspective, MTO companies often keep high raw material inventories to minimize delays (Stavrulaki and Davis, 2010). In MTO products, the procurement of some components and materials occurs after an order is received (Amaro et al., 1999); in ETO, procurement decisions can be made at different stages of the product development. Customers can specify preferred suppliers or present detailed specifications of components, that only a few suppliers can produce. Other parts and components are specified during the detailed design, which often has a big impact on the availability of these parts for manufacturing. Parts and components with long lead times should be considered early in the design process (Hicks et al., 2000). Supply uncertainty is critical, and seen as an obstacle to the fulfilment of the value-adding activities (Gosling et al., 2013).

From the above paragraphs, it is possible to align common sources of uncertainty of the MTO and ETO supply chains with the four sources of uncertainty identified by Mason-Jones and Towill (1998) in the supply chain uncertainty circle: supply side, manufacturing process, demand side, and control systems. These uncertainties can be internal, and occur due to machine breakdowns, labour absenteeism, missing tools, late delivery of parts and rework; and can also be external and driven by the market, due to changing customer requirements, or can be driven by delays in the delivery of materials and components by the suppliers (Babu, 1999). ETO companies operate in such a volatile environment that from one year to another, customer orders can vary more than 50% in volume (Adrodegari et al., 2015). In the ETO manufacturing, added uncertainty exists in the engineering process, due to the spread of activities throughout several participants (Pandit and Zhu, 2007), and possible implementation issues discovered during the manufacturing process, which require the engineering division to change some product specifications. This significantly affects the planning of operations (Caron and Fiore, 1995).

According to Mello et al. (2015), the ETO supply chains encompass three major stages that must be coordinated: tendering, product development, and product realization. Marketing was also considered a major activity in these supply chains (Hicks et al., 2000). These can be divided among non-physical, and physical activities (Hicks and Braiden, 2000, Adrodegari et al., 2015). The non-physical activities include the tendering, engineering, design, contract management, and process planning, while the physical activities include component manufacturing, assembly, and installation/commissioning (Hicks et al., 2000, Hicks and

Braiden, 2000, Adrodegari et al., 2015). MTO companies operate in a similar way (Hicks and Braiden, 2000).

It is during the marketing stage that companies create awareness of themselves and their products. After the company receives a request for a tender by a customer, a preliminary conceptual design and the definition of the major components and systems of the product are made. Contacts with suppliers are established to obtain information about the costs and the lead times for the components. Technical specifications, delivery terms, price, and commercial terms are agreed at this stage. After a contract has been awarded, the company still proceeds with some non-physical activities, as the development of the project plan and the detailed design. Procurement follows, and then the physical process of component manufacturing, assembly, construction, and commissioning (Hicks et al., 2000). Additionally, Adrodegari et al. (2015) defined primary and support activities for ETO companies. Primary activities included: quotation and order management, technical and commercial development, design, purchasing, production, assembly, and testing, delivery, commissioning, and after-sales service. Support activities included: project management, planning, and cost control. Figure 2.2 summarizes the stages and activities of the MTO and ETO value chains. In the context of this work, the marketing stage will not be addressed.

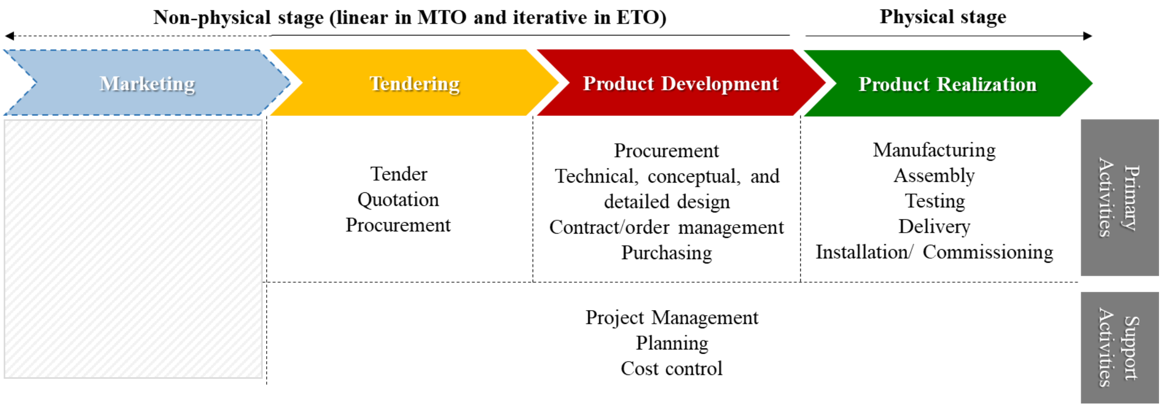


Figure 2. 2. Stages and activities in the MTO and ETO value chains.

Despite the relevance of the MTO/ETO industry sectors, these have received little attention from the manufacturing strategy literature (Hendry, 2010). This is critical given the increasing number of companies supplying customized products and operating in MTO or ETO basis. Indeed, in the past years, and led by the increasing demand for specialized products, the ETO supply chain became a major supply chain structure (Stevenson et al., 2005, Gosling and Naim, 2009). In this sub-section the main features of the MTO and ETO supply chains have been explored. These features are the basis for the development of the manufacturing system models.

2.1.2. Complexity in low volume manufacturing environments

Manufacturing environments characterized by lower volume production experience higher levels of complexity. These complex systems do not allow a one-to-one mapping of inputs to outputs, as in simple systems (Bozarth et al., 2009). Being low volume production environments, MTO and ETO will experience higher levels of complexity, that should be properly understood. There are many drivers of complexity in these environments. First, the products that are manufactured are complex, have multi-level structures, are manufactured and assembled to the customers' specifications (McGovern et al., 1999, Mello et al., 2015, Grabenstetter and Usher, 2015, Addo-Tenkorang et al., 2016), and the fact that customers have a direct participation in the product design results in added uncertainty to these complex products (Addo-Tenkorang et al., 2016). Additionally, a high number of engineering revisions may be handled through manufacturing, due to the overlap of the design and manufacturing activities (McGovern et al., 1999, Mello et al., 2015).

The literature has classified manufacturing complexity along two domains, the functional and the physical (Efthymiou et al., 2012, ElMaraghy et al., 2012). On the functional domain, complexity represents a measure of uncertainty in accomplishing the tasks defined by functional requirements and is closely related to the manufacturing systems design. It can be divided into time independent and time dependent. The time independent complexity can be real or imaginary (ElMaraghy et al., 2012). Real complexity results from not satisfying the functional requirements at all times (Suh, 2005), and imaginary complexity concerns the lack of knowledge about the system (Efthymiou et al., 2012, ElMaraghy et al., 2012). The time dependent complexity can be combinatorial or periodic and occurs when the range of the system moves as a function of time (Suh, 2005). Combinatorial complexity increases as a function of time, while periodic complexity exists in finite periods of time and with a limited number of possible combinations of states (Efthymiou et al., 2012).

There are two types of complexity in the physical domain: static and dynamic. While the first is concerned with the system structure and configuration, the system design (Fredendall and Gabriel, 2003), number and variety of products, and components, labours, machines, buffers, transportations, their interconnections and interdependencies; the dynamic (operational) complexity is related to the uncertainty of the system's behaviour for a given time period and deals with the probability of the system being in control (Efthymiou et al., 2012), and the unpredictability of the system behaviour (Deshmukh et al., 1998) during operation. Dynamic complexity is at least partially determined by the static complexity (Fredendall and Gabriel, 2003). While the static complexity can remain unchanged for long periods of time, the operational complexity is influenced by countless factors, including the changes in demand, the machine breakdowns, and the system control methods (Vrabic and Butala, 2012).

Bozarth et al. (2009) explored the topic of supply chain physical complexity, sub-dividing it in three: internal manufacturing complexity, downstream complexity, and upstream complexity. At the internal manufacturing level, the authors found that potential complexity drivers included the number of supported parts and products, the number of unique parts, the types of manufacturing processes, and the stability of the manufacturing schedules among production periods. Given the features of lower volume production environments, and the identified complexity drivers, higher levels of static and dynamic complexity are expected for these environments. This results from the unique jobs that must be handled, the fact that the manufacturing task may change from one job to the next, which demands more complex interactions between different plant areas, and the higher levels of decentralized decision-making.

Downstream complexity drivers identified by Bozarth et al. (2009), included the number of customers, and their diverse needs, the length of the product life cycle, and the demand variability. Increased downstream complexity is verified for higher number of customers and with more varied needs. The upstream complexity drivers included the number of supplier relationships to manage, the delivery lead time and reliability of suppliers, and the extent of global sourcing. Increased upstream complexity exists for added suppliers, given the increase in the number of relationships that must be managed, the increased number of information and physical flows. This is aggravated by a global supply base. The supplier lead time performance also determines the upstream complexity.

2.2. Manufacturing performance measurement

The dynamism of manufacturing systems increases as the number and type of decisions to be made increase, and the systems integration hinders the prediction of the effect of a decision on the future system performance (Deshmukh et al., 1998). This enhances the relevance of topics as PM, and performance prediction. In this section we start by presenting relevant definitions in the scope of PM, and afterwards explore the critical performance indicators in MTO and ETO environments, the common PM frameworks, and the different methodologies that have been used in the literature for performance assessment.

2.2.1. Relevance and definitions

Measuring performance is a relevant activity for countless purposes. It represents the way of understanding where the organization has been in the past, where it is in the present, where it wants to be in the future, how it is going to get to its objectives, and how it will realize it has achieved its goals (Lebas, 1995). Following the definition by Neely et al. (1995), PM is the process of quantifying an action, with the measurement being the quantification process and action leading to performance. According to this definition PM corresponds to the process of quantifying the efficiency and effectiveness of an action, thus assessing if the customer requirements have been met, and at what cost was a certain level of customer satisfaction achieved (how economically have the firm's resources been utilized?). The PM is nothing more than comparing results against expectations with the final goal of learning to do better (Rouse and Putterill, 2003). One of the most important purposes of PM is delivering reliable information that supports decision-making (Garengo et al., 2005, Ukko et al., 2007, Berrah et al., 2008). PMSs are a vital part of a company's managerial system (Braz et al., 2011). These are multi-criteria (Berrah et al., 2008), balanced and dynamic instruments (Garengo et al., 2005) used for informing decision-makers about a variety of things, including the performance levels, the reasons for good or bad performance, and the criteria for which improvement is necessary (Berrah et al., 2008).

PMSs consist of a set of metrics, or performance indicators, that are used to quantify the efficiency and the effectiveness of actions (Neely et al., 1995, Lauras et al., 2010), in comparison with a target (Braz et al., 2011). A performance indicator is a measure of a manufacturing system's performance (Efthymiou et al., 2014). Measures can be used for countless purposes, depending on the aims and purposes of those using them. These can be used for learning and self-improving, for coordination of actions with partners, and for continuous improvement and control. The motivation for measuring performance varies with the users of the measurement system and their scope of control functions (Lebas, 1995).

Another relevant definition within the scope of PM is that of PM framework. As defined by Folan and Browne (2005), "*The term framework refers to the active employment of particular sets of recommendations: for example, a set of measurement recommendations may suggest the development of a structural framework ... or they may give rise to a procedural framework ...".* PM frameworks are important for aiding in the development of PMSs, by establishing the boundaries and dimensions for PM. Folan and Browne (2005) define two types of PM frameworks, the structural, and the procedural. The first corresponds to frameworks "*... specifying a typology for performance measure management"*, and the second corresponds to frameworks as "*...a step-by-step process for developing performance measures from strategy"*. Frameworks provide ways of thinking about the systems for modelling purposes (Rouse and Putterill, 2003).

As noted by Nudurupati et al. (2011), PM practices have evolved with time. Prior to the 1970s, the management paradigm placed much emphasis on the financial indicators for controlling the different business functions, as sales, productivity, efficiency, and Return on Investment (ROI). During the 1970s, traditional cost accounting models were updated to reflect the business environment during these years. In the 1980s, and given the success of the Japanese techniques, new dimensions of the business performance started being considered, including quality, time, cost, and flexibility. Academics and practitioners recognized the need to change traditional measurement based on accounting systems to accommodate new manufacturing philosophies and dimensions. During the late 1980s and 90s, traditional financial measures were severely criticized, given their internal and historical data-based foundations. Given the modern demanding context of competitive markets, businesses across different industries have been facing challenges imposed by customers requiring more sophisticated products and services. To comply with these requirements, companies must become more responsive to the market needs, employ more flexible processes, have more flexible suppliers and better coordinated supply chains, alongside reducing costs. To achieve these objectives, management must have accurate, dynamic, integrated, accessible, and visible information to allow faster decision-making and promote a pro-active management style. Managers need predictive measures that allow envisioning what will happen in the future: next week, month, or year.

2.2.2. Performance measurement frameworks

Throughout the years, several PM frameworks have been proposed. According to Santos et al. (2018) the use of these PM frameworks has been extensively documented and several authors have reported a successful implementation of these recommendations. Despite this, other authors have emphasized the failure of these frameworks in supporting the decision-making process. Considering the works by (Garengo et al., 2005, Folan and Browne, 2005, Hon, 2005), Table 2.1, though not being and extensive documentation of the literature, summarizes some of the most important PM frameworks proposed in the literature.

Table 2. 1. Performance measurement frameworks

Framework	Authors	Reference	Short description
Performance Criteria System	Shlomo Globerson	(Globerson, 1985)	Sets recommendations for the development of PMSs, such as the selection of criteria to be evaluated and the measurement frequency
Performance Measurement Matrix	Daniel Keegan, Robert Eiler, and Charles Jones	(Keegan et al., 1989)	Aids a company in establishing its strategic objectives and translating these into performance measures, by examining external and internal environments, and cost and non-cost performance measures in two-by-two matrix
Performance Pyramid (SMART)	Richard Lynch, and Kelvin Cross	(Lynch and Cross, 1991)	Represents an attempt to incorporate financial and non-financial indicators in a PMS in a hierarchy of 4 levels, from the corporate vision to the departments' indicators, and internally and externally focused indicators
Results and Determinants framework	Lin Fitzgerald, Robert Johnston, Stan Brignall, Rhian Silvestro, and Christopher Voss	(Fitzgerald et al., 1991)	Performance indicators are classified into two types, including those concerning the results (e.g. financial performance), and those focusing on the determinants of the results (e.g. quality, innovation, flexibility), and is directed for service companies
Balanced Scorecard	Robert Kaplan and David Norton	(Kaplan and Norton, 1992)	Integrates four perspectives of performance – financial, customer, internal business, and innovation and learning - , connecting the performance measurement and the organization's strategy
Performance Prism	Andy Neely and Chris Adams	(Neely and Adams, 2000)	It is represented by a three-dimensional prism that intends to assess the performance of the whole organization, by considering the stakeholder satisfaction, strategies, processes, capabilities, and stakeholder contributions
Performance Measurement System	David Medori and Derek Steeple	(Medori and Steeple, 2000)	A set of recommendations for the selection, implementation, and auditing of performance measures, considering industry design requirements
Integrated Performance Measurement System	Umit Bititci, Allan Carrie, and Trevor Turner	(Bititci et al., 2002)	Auditable integrated performance measurement system, considering the business, business units, business processes, and activities
Integrated Performance Measurement Framework	Paul Rouse and Martin Putterill	(Rouse and Putterill, 2003)	Integrates several literature frameworks and illustrative models for performance measurement, and derives sets of principles for performance measurement

Among the PM frameworks in Table 2.1, the Balanced Scorecard (BSC) is the most commonly applied worldwide, given its strengths in translating strategic objectives into performance measures and actions (Braz et al., 2011). The BSC presents a financial performance view which is complemented by non-financial performance measures. Despite this, there is not an overload of performance measures, as there is a push to focus on the critical measures (Tangen, 2004). Yet, the framework is not flawless. It lacks a competitive dimension, it does not address the human resources and supplier performances, and does not specify the dimensions of performance that drive success (Rouse and Putterill, 2003, Kennerley and Neely, 2002). Additionally, it is primarily directed to senior managers and not to the shop floor (Tangen, 2004). Other frameworks address these issues but have downfalls in other dimensions. The Performance Measurement Matrix, despite combining cost and non-cost perspectives, with the internal and external perspectives, is often seen as over simplistic, as it does not consider the relationships that are considered by other frameworks (Garengo et al., 2005), as the Performance Prism. Also, it does not reflect all the attributes that are increasingly needed to consider (Kennerley and Neely, 2002), in complex environments, as the systems dynamics. In what concerns to the Performance Prims, it has a great advantage in aiding establishing a strong foundation for the performance measures; however, it offers little guidance on how the performance measures will be understood (Tangen, 2004). The Performance Pyramid, despite being a valuable attempt in integrating the corporate objectives with operational performance indicators, does not provide a way to identify the key performance indicators, nor a way to integrate the continuous improvement concept (Tangen, 2004). The Medori and Steeple (2000) framework has the advantage of being able to be used for the design of a new PMS, but also for enhancing existing PMSs.

Traditional approaches to PM have been severely criticized due to the single profitability dimension of performance that is commonly addressed (Tangen, 2004). PM frameworks are relevant tools that aid in the development of the critical performance indicators, aligning the strategic objectives with the business operations, and supporting the decision-making process. From the analysed PM frameworks, it is possible to conclude that these frameworks should be multidimensional and multi-level (though the number of performance measures should be limited to the relevant ones), as there are many relevant aspects that must be assessed (e.g. customers, firm resources) across different decision-making levels; should be aligned with the organization's strategic intentions, should simultaneously reflect the internal and external environments, must reflect the causality among the factors driving performance, and must reflect all attributes that are critical for the business success. These frameworks are often seen alongside performance measurement/assessment models, used to explain or predict the behaviour of system components of interest, which are explored in the following section.

2.2.3. Types of models for performance assessment and contextual gap

While the PM frameworks described in the previous sub-sub-section provide ways of thinking about a system for modelling purposes, the models of a system represent attempts to predict the behaviour of the system components of interest (Rouse and Putterill, 2003). Indeed, it has been noted several years ago that having these formal models capable of predicting the systems' performance and identifying the key factors affecting performance were critical for success (Buzacott, 1985). Also, modelling frameworks have been referred in the literature as important tools for the assessment of the dynamic behaviour of systems and supply chains (Özbayrak et al., 2007).

Considering that prediction is a key feature for a successful performance assessment (Wilcox and Bourne, 2003), varied models for performance measurement, improvement, and control, using different quantitative Operations Research (OR) techniques have been proposed in the literature. Fuller and Mansour (2003) identified a set of 13 quantitative techniques for developing models in OR. These techniques included decision analysis, linear programming, game theory, simulation, network optimization, project management, inventory, queuing, dynamic programming, integer programming, non-linear programming, forecasting, and Markov decision models (Fuller and Mansour, 2003), as in Figure 2.3. Each referred technique has different goals, strengths and limitations that should be properly understood and addressed upon the development and implementation of a PM model. Some of the techniques discussed, though not having a direct role in performance assessment *per se*, have had a relevant role in improving the performance of manufacturing systems, e.g. inventory models. Others have been mostly used for performance monitoring and prediction purposes, as the linear programming and simulation. In the following paragraphs we explore each referred technique for the purposes of PM, by providing examples of their use for performance assessment/improvement, their strengths and limitations.

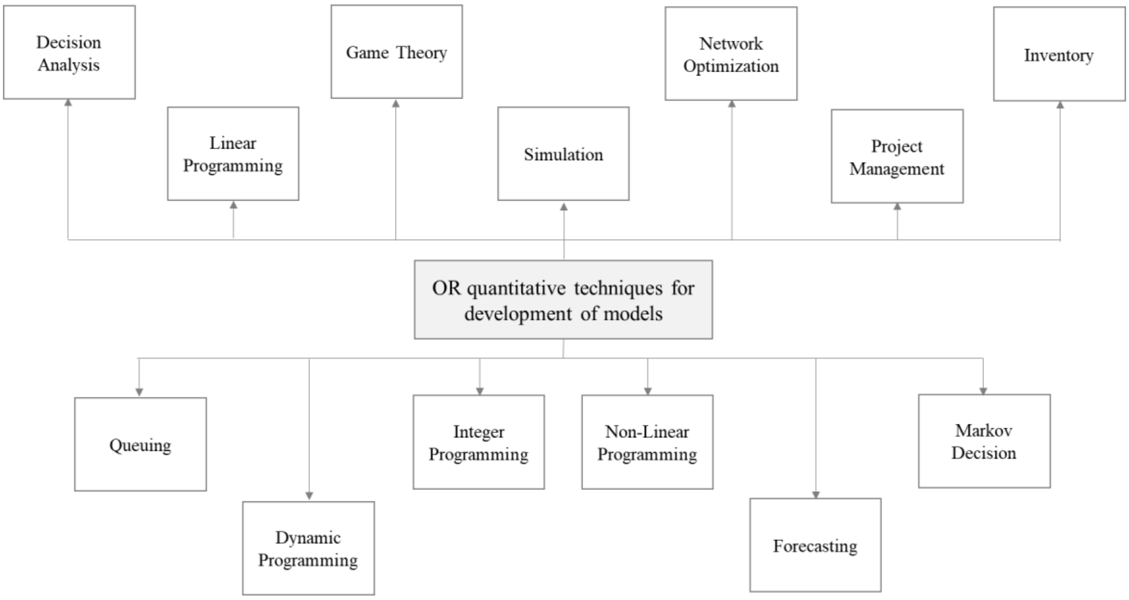


Figure 2. 3. OR quantitative techniques for the development of models that can be used for performance assessment.

Decision analysis models are those that consider states and their associated probabilities and different outcomes for the purpose of selecting the most advantageous alternative (Fuller and Mansour, 2003). These models help identifying the best or optimal decision alternative, given information about uncertain events and the possible consequences of those events (Anderson et al., 2013). Tools as decision trees, probabilistic forecasting, and Multiattribute Utility Analysis are used (Ulvila and Brown, 1982). Examples of the use of decision analysis for performance measurement include the works of Delen et al. (2013), which considered the use of exploratory factor analysis and decision tree algorithms for measuring the firm performance with financial ratios; the work by Youngblood and Collins (2003) that combined the use of the BSC with Multiattribute Utility theory for the development of a quantitative tool for the assessment of trade-offs between performance metrics; and the work by Kim and Reinschmidt (2010) that proposed a forecasting method based on the Kalman filter to obtain the probabilistic predictions of a project duration. Decision analysis models bring many advantages, as making dialog easy among decision makers, evaluating several alternatives, including uncertainties, and providing a way to assess alternatives that could otherwise have been overlooked, leading to well-informed decisions (Keeney, 1982). Despite these advantages, even a careful decision analysis can lead to uncertain final consequences of actions given the occurrence of an unlikely future event. This requires an associated risk analysis (Anderson et al., 2013). Additionally, there is the need to consider the multiple objectives of the decision makers, the multiple groups that are affected by the outcomes of the decisions, and the difficulty and need for creativity in identifying good alternatives for problems (Keeney, 1982).

Linear programming models consist of sets of linear equations that are used for optimally allocating limited resources to competing demands (Fuller and Mansour, 2003). A typical performance measurement tool that uses linear programming techniques to estimate the relative efficiency of Decision Making Units (DMUs) in the presence of multiple inputs and outputs, is the Data Envelopment Analysis (DEA) (Cook et al., 2014). It is the among the best known tools for performance measurement (Santos et al., 2018). It is considered a powerful benchmarking tool for manufacturing and service operations (Cook et al., 2014). Several works have been using DEA for the purpose of assessment of the energy efficiency, as reported by Mardani et al. (2017), and for the internal supply chain performance measurement (Wai and Kuan, 2007). Other uses of linear programming models have been reported by Stricker et al. (2017), for the selection of performance indicators, and by Kumar et al. (2017) for the allocation of orders among suppliers, considering different sustainability performance indicators. Linear programming models as DEA bring several advantages to PM, including being able to handle multiple input and output models, not requiring an assumption of a functional form relating inputs to outputs, which can have different units, and allowing direct comparison of DMUs. However, DEA is very much affected by noise due to being an extreme point technique, it converges slowly in estimating the absolute efficiency of a DMU, as it is a nonparametric technique, it diffuses the elaboration of hypothesis tests, large problems can be computationally intensive given the separate linear programs for each DMU, and as a linear programming tool, it does not ensure that all the weights of criteria are considered (Fox, 2017), nor uncertainty. Linearity assumptions can be problematic.

Game theory models are used for representing business management games, imbedding two or more players in a simulated business environment. The players have to make decisions in certain moments of the game to maximize their returns, and the decisions that the players make in a certain time will affect the conditions under which subsequent decisions will be made (Fuller and Mansour, 2003). Game theory does postulate some rules under which the individuals act, otherwise it would not have a predictive capability (Koçkesen and Ok, 2007). Examples of works incorporating game theory models for performance measurement include those of Jalali Naini et al. (2011), which combined the use of evolutionary game theory and the BSC, and from Eskafi et al. (2015), which combines the BSC, path analysis, cooperative game theory, and evolutionary game theory. Game theory models are very accurate, given their mathematical formulation. Given the reliance on psychology information, game theory models become closer to the human behaviour, facilitating the empirical testing of the models (Epstein and Manzoni, 2008). The basic assumptions of game theory models, including that information about the game rules is complete and available to all players, information is perfect and all players are informed about others' decisions, all decisions are made under rationality for maximizing the player's utility function, behaviour is competitive and non-cooperative, players and environmental factors are dynamic, the interdependence of the results obtained by each player, the result of the game being affected by the length of the game and the attempt to establish equilibrium between the players, have been subject to criticism. These assumptions do not always reflect real world situations. Examples are those that of all decisions intending to maximize the utility function, and that complete information is available at all times (Dominici, 2011).

Simulation models are used for modelling the behaviour of a real a system and retrieve statistical results about the operations of the system (Fuller and Mansour, 2003). As defined by Kelton et al. (2003), simulation consists in a "*…broad collection of methods to mimic the behaviour of real systems, usually on a computer with appropriate software.*". The use of simulation models allows modelling the manufacturing complexity and measuring the impact of operational decisions in the future system's performance (Efthymiou et al., 2014). While mathematical modelling of manufacturing systems can be quite challenging, due to the intricate relationships and interrelations among the system's elements, alongside the stochastic nature of the system, that is characterized by unpredictability (Efthymiou et al., 2012), simulation models allow users to observe and analyse the dynamic behaviour of the target system. Simulation models have been used since 1960 for supporting performance analysis of manufacturing systems (Umeda and Zhang, 2006). These are well-suited for assessing dynamic decision rules under different 'what-if' scenarios (Min and Zhou, 2002), and allow the detailed representation of the operation of a system, including the machines, jobs, workflow, job routes, and sequencing rules. With this, performance predictions become very accurate. Simulation models, while capturing with high detail the system, can have a lengthy development. An adequate validation of the models can also take a substantial time, and sometimes is difficult to ensure that the model adequately captures the system (Buzacott, 1985), and simulation models do not guarantee optimal solutions (Stefanovic et al., 2009). Simulation as a research tool is often used based on the superior relevance of the problem being analysed rather than based on the scientific relevance of the results obtained (Bertrand and Fransoo, 2002). Despite these drawbacks, many simulation models for performance measurement have been proposed in the literature. Examples include the work of Özbayrak et al. (2007) that proposed an SD model for the assessment of the MTO supply chain performance, considering the key metrics of inventory, WIP levels, backlog orders, and customer satisfaction, across the different supply chain echelons; and the work of Ramasesh et al. (2001) that proposes a framework for the analysis of the manufacturing system and a simulation model for facilitating performance appraisal.

The network optimization models are used for solving location-allocation problems, through a graphical description of a problem. These enable solving problems in transportation systems design and project scheduling (Fuller and Mansour, 2003), and are a special type of linear programming models whose major classes of problems include the minimum cost flow problem, the single commodity network flow problem with convex cost, the multicommodity network flow problem with linear or convex cost, and the discrete network optimization problems (Bertsekas, 1998). These models can be applied at different levels of decision making – strategic, tactical, and operational. At the strategic level, are used for supply chain design, at the tactical level for aggregate inventory and transportation policy decisions; at the operational level on the structuring of vehicle routings and allocation of inventories to customer demands. These models have been widely used for optimizing the performance of the supply networks (Geunes and Pardalos, 2003).

In what concerns to project management models, these are graphical representations that allow monitoring the execution of projects in terms of time, cost, and effort. Project management models include the use of techniques as the Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) (Fuller and Mansour, 2003). These techniques have a major difference concerning the times considered for the jobs. While the CPM considers a unique time for every job, being used for deterministic projects; the PERT considers three estimates of activities time (optimistic, pessimistic, and most likely), being used for stochastic projects. Simulation, specifically System Dynamics (SD) has also been used for project management models, presenting a valuable alternative in representing feedback loops and other interactions that are not commonly considered in traditional project management techniques as the PERT and CPM (Rodrigues and Bowers, 1996, Rodrigues et al., 2006).

Inventory models are concerned with the maintenance of inventories – costs of carrying, ordering, and purchasing (Fuller and Mansour, 2003). Appropriate inventory management is critical to achieve the desired flexibility in production planning and scheduling. Indeed, publications as Vedran et al. (2009) have stressed the influential factors among inventory performance and financial performance. Inventory models as MRP and Manufacturing Resources Planning (MRP II) have been developed for enhancing manufacturing productivity and increase competition (Stamm et al., 1989).

Queuing models are predictive models that allow studying the behaviour of a system with waiting lines. The goals of these models are improving or speeding up the service and increasing the efficiency of service centres (Fuller and Mansour, 2003). These queuing models are a relevant tool for studying the dynamic behaviour of stochastic service systems, including manufacturing systems. Different performance measures can be computed by the use of queuing models, including job tardiness, flow time, and WIP (Tate, 1990). Simulation models are often used for the assessment of queuing models.

Dynamic programming models break a large problem into smaller problems that, when solved, lead to an optimal solution for the large problem (Fuller and Mansour, 2003). In the manufacturing and network domains, dynamic programming has been used in problems as the optimal design of stochastic production lines with cost minimization (Donohue et al., 2002), assembly line balancing (Quyen et al., 2017), or the layout optimization of interconnection networks (Tripathy et al., 2015). Dynamic programming becomes intractable when problems which have a practical scale are considered (Farias and Roy, 2003).

Integer programming models are commonly used for problems that can be considered as linear programs, whose decision variables are integer values (Fuller and Mansour, 2003). These problems can be mixed integer when some of the variables must be integer or can be pure integer programs when all variables must be integer. These models have been used in many applications, including warehouse location (Bradley et al., 1977a) and scheduling (Sawik, 2005). Unlike in linear programming models, nonlinear programming models do not assume that the functions that constitute the problems are linear (Fuller and

Mansour, 2003). Nonlinear programming models have been used in applications as portfolio selection, resource planning (Bradley et al., 1977b), or modelling of flexible manufacturing systems (Yadav and Jayswal, 2018).

Forecasting models are often used for predicting the future of a business operation (Fuller and Mansour, 2003). Quantitative forecasting uses the firm historical data to make projections into the future. Different forecasting techniques can be combined to improve the outcomes of the prediction (Chindia et al., 2014). Quantitative forecasting can be divided in time series analysis and causal modelling techniques. In the time series approach, the pattern of past behaviour of a single phenomenon over time is assessed, considering the reasons for variation in the trend, and to forecast the future behaviour. Simple time series analysis includes moving average and exponential smoothing. Causal modelling considers the complex cause-effect relationships, by considering multiple variables and relationships. Structural equation modelling is a causal modelling forecasting technique (Slack et al., 2010).

Markov decision models are used for studying the evolution of systems over repeated trials, and understanding their behaviour over time (Fuller and Mansour, 2003). The objective is to determine a rule at each decision made at a point of time that maximizes the performance of the system, which is expressed by a utility function. It is the role of the decision maker finding the optimal balance between the immediate reward and the future reward. Several applications of Markov decision theory can be found in the routing, replacement, maintenance and repair, inventory, optimal control of queues, and stochastic scheduling problems (Feinberg and Shwartz, 2012). Markov modelling provides many advantages, including the easiness in expressing the dynamic system behaviour, possibility of modelling behaviour involving complex repair of components, and modelling of sequence dependent behaviour. Despite this, Markov models can be difficult to validate, especially when a large number of states are required. When the behaviour of the system is too detailed or complex and an estimation of detailed performance behaviour is needed, other approaches, as simulation, should be preferred (Boyd, 1998).

Models for performance measurement considering other Multiple Criteria Decision Making (MCDM) approaches and heuristics have also been proposed. These include techniques as the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Neural Networks (NN), and Genetic Algorithms (GA). Montagno et al. (2002) developed a GA trained NN for predicting the combinations of performance improvement initiatives associated with performance improvements. Cho et al. (2012) used fuzzy AHP to prioritize performance measurement indicators in a service supply chain. Bhattacharya et al. (2014) used the fuzzy ANP BSC based approach for the green supply chain performance measurement. As AHP and ANP are partially qualitative methodologies (Balfaqih et al., 2016), will not be further considered in this work for the model development *per se*, but as supplemental tools of the simulation models. Artificial NN, despite being relatively easy to implement, have limitations including the difficulty in achieving an optimal training set for the NN, the configuration of the NN is time consuming, and the knowledge representation can be vague (Huang and Zhang, 1994). These are black boxes, which raises concerns towards the ability of the NN to generalize to situations not reflected in the data set (Chowdhury and Sadek, 2012).

The features of the different techniques for the development of models and their common applications in the PM domain, make them fit for different requirements. In the context of this research work, the requirements for the PM models arise from the desirable features of a predictive performance assessment model, and from the needs imposed by the MTO/ETO manufacturing environments. For each requirement, a set of criteria is established to classify the techniques in three levels: considers/contains (C), partially considers/contains (PC), and does not consider/contain (DNC). The requirements and the criteria are presented in Table 2.2. If the technique is designed in a way that it complies with all the criteria, it is classified as a C; if it complies with at least one of the criteria, it is classified as PC; if none of the criteria are met, the technique is classified as DNC. The classification of the techniques for each requirement is presented in Table 2.3. The classifications established in Table 2.3 resulted from the analysis of papers using the technique for PM purposes. Despite this, the classification has been established on an empirical basis, and for the purpose of understanding which technique was the best fit for the objectives of this research work.

Table 2. 2. Requirements for the techniques from the PM perspective and the from the MTO/ETO environments and classification criteria

Requirements		**Criteria**
PM perspective	Predictive capability	1. Capable of making future predictions with a certain degree of uncertainty; 2. Forecast the outcomes of an action; 3. Possibility of thorough exploration of alternatives.
	Quantification capability	1. The output of the model is quantitative; 2. The output of the model is comparable with other quantitative measures; 3. The quantitative data is unambiguous.
	Use of multidimensional indicators	1. More than a single performance indicator is assessed; 2. A single model run can provide estimates of more than one indicator; 3. The model focuses on indicators spread through different categories.
	Easy access to information/ visibility	1. The model output is easily communicable; 2. The model output does not require extensive statistical analysis; 3. The output of the model promotes discussion.
	Flexibility	1. The model serves multiple purposes; 2. The model is easily modifiable; 3. The model represents varied activities of the modelled system.
	Accurate representation of the system behaviour	1. The model represents the behaviour of the system; 2. The model structure has a close relationship with the structure of the modelled system; 3. The model assumptions are realistic.
MTO/ETO manufacturing environments	Dynamic representation of the manufacturing environment	1. The model evolves as the status of the manufacturing system evolves; 2. The model adapts to new circumstances; 3. The model represents the dynamic behaviour of the system operations.
	Use of stochastic variables	1. The model can include stochastic variables; 2. Stochastic variables are used to represent uncertainty; 3. The stochastic variables have correspondence with real variables (e.g. demand).
	Product development modelling, and modelling of manufacturing activities with different nature	1. Product development activities can be modelled; 2. Activities with different nature can be represented in the same model environment; 3. The varied activities are linked and have a relevant contribution to the model.
	Comply with partially available data	1. The model runs with partially available data; 2. The model can make its own estimates of data/ produce its own data; 3. The behaviour of the model remains acceptable with different data sets.
	Capability to represent the modelled system complexity	1. The model can represent complex interactions among activities; 2. Multiple levels of activities with different degrees of complexity can be represented; 3. The model can represent the system complexity in terms of the product, process, and operations.
	Time representation	1. The model results present the evolution of the performance measures with time; 2. The model can run considering different time horizons; 3. The model can represent activities that have different duration in time.
	Represent multiple levels of system analysis	1. The model can represent varied levels of operations (e.g. production and supply chain); 2. The model complies with different levels of data aggregation; 3. The model represents different levels of decision-making.

Table 2. 3. Techniques used for performance assessment models and their compliance with requirements from the PM and MTO/ETO manufacturing environments, perspectives (DNC – does not consider/contain; PC – partially considers/contains; C – considers/contains)

Techniques used in performance assessment models	Requirements from the PM perspective																								Requirements from the MTO/ETO manufacturing environments																											
	Predictive capability				Quantification capability				Use of multi-dimensional indicators				Easy access to information/ visibility				Flexibility				Accurate representation of the system behaviour				Dynamic representation of the manufacturing environment				Use of stochastic variables				Product development modelling, and modelling of manufacturing activities with different nature				Comply with partially available data				Capability to represent the modelled system complexity				Time representation				Represent multiple levels of system analysis			
	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total	1	2	3	Total
Decision Analysis	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	✓	✓	×	PC	×	×	✓	PC	×	×	×	DNC	✓	✓	✓	C	×	×	×	DNC	✓	×	✓	PC	×	×	×	DNC	×	×	×	DNC	×	×	✓	PC
Linear Programming	✓	×	×	PC	✓	✓	✓	C	✓	✓	✓	C	×	×	✓	PC	✓	✓	✓	C	×	×	✓	PC	✓	✓	×	PC	✓	✓	✓	C	×	✓	×	PC	×	×	✓	PC	✓	✓	×	PC	×	×	×	DNC	✓	×	×	PC
Game theory	✓	✓	×	PC	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	×	×	✓	PC	×	×	×	DNC	✓	✓	✓	C	×	✓	×	PC	×	×	×	DNC	×	×	×	DNC	×	✓	×	PC	✓	×	✓	PC
Simulation	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	×	×	✓	PC	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	×	✓	✓	PC	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C
Network optimization	×	×	×	DNC	✓	✓	✓	C	✓	✓	✓	C	×	✓	✓	PC	×	✓	×	PC	×	×	✓	PC	×	×	×	DNC	✓	✓	✓	C	×	×	×	DNC	×	×	✓	PC	×	✓	×	PC	×	×	×	DNC	✓	✓	✓	C
Project management	✓	×	×	PC	✓	✓	✓	C	×	×	×	DNC	✓	✓	✓	C	×	✓	×	PC	×	×	✓	PC	×	✓	×	PC	✓	✓	✓	C	✓	✓	✓	C	✓	×	✓	PC	×	✓	×	PC	✓	✓	✓	C	×	×	×	DNC
Inventory	✓	×	✓	PC	✓	✓	✓	C	×	×	×	DNC	✓	✓	✓	C	×	✓	×	PC	×	×	✓	PC	✓	✓	✓	C	×	×	×	DNC	×	×	×	DNC	×	×	×	DNC	×	×	×	DNC	×	✓	✓	PC	×	×	×	DNC
Queuing	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	×	✓	×	PC	✓	×	✓	PC	×	×	✓	PC	✓	✓	✓	C	×	×	×	DNC	×	×	✓	PC	✓	×	×	PC	✓	✓	✓	C	×	×	×	DNC
Dynamic programming	✓	×	×	PC	✓	✓	✓	C	✓	✓	✓	C	×	×	✓	PC	✓	✓	✓	C	×	×	✓	PC	✓	✓	×	PC	✓	✓	✓	C	×	✓	×	PC	×	×	✓	PC	✓	✓	×	PC	×	×	×	DNC	✓	×	×	PC
Integer programming	✓	×	×	PC	✓	✓	✓	C	✓	✓	✓	C	×	×	✓	PC	✓	✓	✓	C	×	×	✓	PC	✓	✓	×	PC	✓	✓	✓	C	×	✓	×	PC	×	×	✓	PC	✓	✓	×	PC	×	×	×	DNC	✓	×	×	PC
Non-linear programming	✓	×	×	PC	✓	✓	✓	C	✓	✓	✓	C	×	×	✓	PC	✓	✓	✓	C	×	×	✓	PC	✓	✓	×	PC	✓	✓	✓	C	×	✓	×	PC	×	×	✓	PC	✓	✓	×	PC	×	×	×	DNC	✓	×	×	PC
Forecasting	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	✓	×	×	PC	×	×	✓	PC	×	×	×	DNC	×	×	×	DNC	×	×	×	DNC	×	×	✓	PC	×	×	×	DNC	✓	✓	✓	C	✓	×	✓	PC
Markov decision	✓	✓	✓	C	✓	✓	✓	C	✓	✓	✓	C	×	×	✓	PC	✓	✓	✓	C	✓	×	✓	PC	✓	✓	✓	C	✓	✓	✓	C	×	×	×	DNC	×	×	✓	PC	×	✓	×	PC	✓	✓	✓	C	×	✓	×	PC

For the research objectives established in this work, a simulation approach was deemed the most appropriate, as it responds to most requirements established for the performance assessment in complex manufacturing environments. Notwithstanding this, within a simulation approach, relevant inventory, planning, scheduling, and resource assignment tools are needed. For this and given the complexity of the modelling and simulation process for manufacturing environments, simple business rules/heuristics – deemed relevant from the literature analysis - have been considered for these purposes. In section 3, the use of the simulation approach will be detailed.

2.2.4. Performance indicators

Upon modelling systems for PM, a critical stage is determining the modelling objectives. Without this, it is impossible to develop the appropriate performance indicators that will reflect the system behaviour of interest. For this, the model builder must identify the key components to be modelled, alongside the relevant performance indicators (Min and Zhou, 2002). It is the role of the performance indicators reflecting the current state of the manufacturing systems' situation so that monitoring and control of the operational efficiency become possible (Efthymiou et al., 2014).

Meyer (2003) refers that performance indicators have seven purposes: look ahead, look back, motivate people, compensate people, compare across businesses and functional units, roll up from the bottom to the top of the organization, and cascade down from the top to the bottom. This means that performance indicators should be related to the different hierarchical and organizational levels, should be linked to the decision-making processes and give control over the lowest levels of the organizational hierarchy (Braz et al., 2011). The most traditional performance indicators were developed from the cost accounting systems. Many limitations have been pointed to these financially-based indicators, as encouraging short termism, lacking strategic focus, not encouraging continuous improvement, and not being externally focused (Bourne et al., 2000). Despite this, and as pointed by Meyer (2003), though financial indicators are more concerned with capturing the results of past performance, these are still important as they allow to look ahead, affect the firm's cost of capital and reputation. These measures have a key role in motivating people and in driving their compensation; can cascade down from the top of the individual business units to permit performance comparisons across business units and roll up from the individual business units to the top of the organizations.

Notwithstanding the relevance of the financial performance indicators, several improvements have been proposed through time to include a multidimensional balance of the indicators used when assessing performance (Bourne et al., 2000). The PM goals should, most of all, reflect the organizational goals and encompass a balance between financial and non-financial measures, that can be related to the strategic, tactical, and operational levels of decision-making and control (Gunasekaran et al., 2004). There are countless non-financial indicators that can target different business functional units, as new product development, marketing, and operations. The limitation of the non-financial metrics is that some of them cannot be applied across functional units and, therefore, functional units cannot be compared. Nonfinancial indicators will, for this, measure the performance of the functional unit, but not the business unit or the firm (Meyer, 2003).

Braz et al. (2011) emphasized a set of features that make good performance indicators. These features include being quantitative, have objective values, being easy to understand, allowing faster identification of what is being measured and how it is being measured, using appropriate scales, being consistent, maintaining meaning over time, having clear objectives, encouraging adequate behaviour, being visible to everyone involved in the process, measuring only what is relevant, and demonstrating existing trade-offs. Lauras et al. (2010) highlight that performance indicators should be simple, predictive and pervasive.

In the literature, the authors have identified different major classes of Competitive Priorities (CPs) in which performance indicators can be included. These are quality, time (delivery speed and delivery reliability), flexibility, and cost (Neely et al., 1995, Lauras et al., 2010, Efthymiou et al., 2014). Adding to this classical approach to the classification of competitive priorities, other classes are nowadays becoming relevant, as the environmental and social sustainability (Longoni and Cagliano, 2015). The quality CP, from the product perspective focuses on the conformance to the specifications, the number of defects produced and the cost of quality. The customer satisfaction is another relevant quality indicator. Time is an important source of competitive advantage and usually reflects how quickly and how dependably the products are delivered to customers. Flexibility can be measured through different indicators, including mix flexibility, that corresponds to the number/range of components handled by the equipment. It can also be measured as the average volume fluctuations that occur in a given time frame by the capacity limit. Measures of cost can have a different focus. One example is productivity (Neely et al., 1995). At the production level, production costs can be divided into materials, labour, and machinery (De Toni and Tonchia, 2001). From a supply chain perspective, Pettersson and Segerstedt (2013), divided the supply chain cost into six major areas, including manufacturing, administration, warehouse, distribution, capital, and installation cost. The authors highlight the fact that the relevant cost areas will vary according to the type of supply chain. The manufacturing costs include material, direct labour and overhead production costs. The administration costs cover all costs related to customer order handling, people who purchase materials and book transportation. Warehouse costs cover the stockholding costs and treatments in warehousing. Distribution costs include the inbound and outbound transportation and its administration. Capital costs include investments in the company facilities; and installation costs are those costs associated with the activities undergone by companies that install their products at the customers' locations.

From a manufacturing/supply chain strategy perspective, the CODP location will determine the performance indicators that are critical to the business success. For operations downstream the CODP, there is a higher emphasis on the productivity of the operations (Rudberg and Wikner, 2004), while upstream the CODP emphasis is on flexibility, across multiple dimensions – product, assembly, workforce, supplier -, and compliance with customers' specific requirements (Rudberg and Wikner, 2004, Gosling and Naim, 2009). For an MTO/ETO manufacturer, the ability to customize products is a capability taken for granted by customers, not constituting an order winner (Gosling and Naim, 2009). It is core for low volume manufacturers, ensuring the highest quality of service to attain customer satisfaction (Stavrulaki and Davis, 2010). Time is also an important competitive dimension for MTO and ETO manufacturers, as it is not unusual that customers impose large cost penalties for lateness (Grabenstetter and Usher, 2015).

Following Olhager (2012) it is evident that in MTO and ETO environments the relevant competitive criteria are based on quality, delivery, and flexibility. Order winners are usually associated with some aspect of flexibility and delivery speed; quality and delivery are usually market qualifiers. While price can be a qualifier for some products, for others the price is irrelevant.

2.3. Performance determinants in MTO and ETO

In the MTO/ETO environments, multiple products are being developed simultaneously, in diverse stages of development and for different customers with varied requirements (Rahim and Baksh, 2003). This adds to the need of properly identifying the key elements that determine the performance of MTO and ETO projects. Indeed, an effective management of operations and development of operations strategy is much dependent on a proper understanding of the determinants of performance (Silvestro, 2014). Following the definition of determinant given by the Merriam-Webster dictionary (Merriam-Webster), "*an element that identifies or determines the nature of something or that fixes or conditions an outcome*", in this section we identify the critical determinants that can cause performance variations in these manufacturing environments.

Though companies specialize in particular product types and gather specific technical competencies (Rahim and Baksh, 2003), during a project development, the size of a project will be an important factor for performance. This is because larger projects tend to be more complicated to coordinate, and are usually subject to more customer order changes (Mello et al., 2015). As ETO products can encompass varied degrees of standardized and customized BOMs from order to order (Gosling and Naim, 2009), order repeat is possible for some products, and the same design and production processes can be used (Rahim and Baksh, 2003). An ETO product will usually include components that need to be newly designed and engineered and predefined components. This translates in different design and engineering efforts (Lu et al., 2009). Hence, knowledge reuse is very important for reducing the product development cycle (Mourtzis et al., 2014). Lots of knowledge are already available in ETO environments. Reuse of product components can be extremely useful. By reusing design concepts adapted to the new products, new customer orders could be regarded as a problem solved by looking for similar cases and adapting solutions (Amrani et al., 2010). Outsourcing of parts and/or components is also seen as a means for reducing the internal BOM for companies (Olhager and Wikner, 2000).

Gosling et al. (2013) identified multiple uncertainties for the ETO sector, more specifically for the construction sector. Despite this, some of the uncertainties identified by the authors can be applied to other project environments. These uncertainties are determinants of performance that were classified by the authors according to the likelihood and impact, and were segmented by process, control, supply, demand, and external. While the external uncertainties were specific of the construction sector, process, control, supply and demand uncertainties could easily translate to other environments. Process uncertainties included the volatility of the workflow, the speed of construction, and the accuracy of the project plan; timely/correct information from clients was identified as a control uncertainty; supplier uncertainties included early/late deliveries and the timely/correct info from suppliers; and demand side uncertainties included the late changes to specifications and the use of new technology. As referred by Mello et al. (2015), the maturity of the design/technology is also an important factor. For projects in which the solutions adopted the maturity of the technology is lower, there is a higher need for adjustments, particularly during the production.

From the above, a set of six performance determinants can be identified: design/engineering workload, project type, design reuse, outsourcing, complexity, and experience/knowledge of technology. These performance determinants are represented in Figure 2.4.

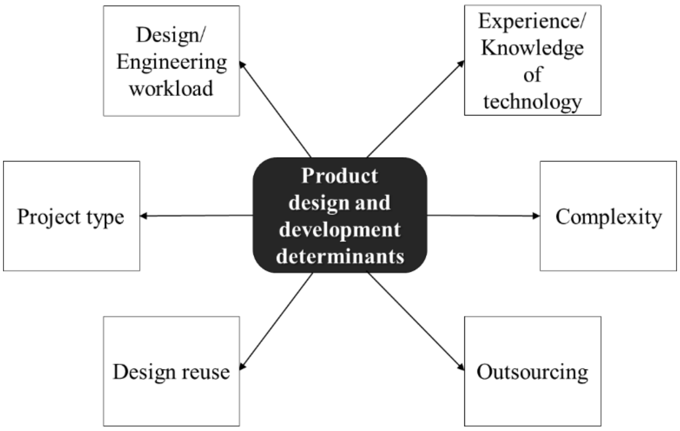


Figure 2. 4. Performance determinants in the MTO/ETO manufacturing environments.

Each determinant has been defined as follows:

1. Design/Engineering workload: Number of design objects to be considered for the design/engineering tasks;

2. Project type: Number of product families/product types that will be integrated during the project development;
3. Design reuse: Percentage of sub-systems/components whose design will be reused and don't have to be designed from scratch;
4. Outsourcing: Percentage of sub-systems/components that will be designed and produced in outsourcing;
5. Complexity: Expected product integration challenges, product operationalization, rework, and manufacturing tasks relative difficulty;
6. Experience/knowledge of technology: Familiarity with the technology being used for the product under development.

The above referred performance determinants should be considered in the PM models developed, by influencing model variables that have an impact in the execution and coordination of the modelled tasks. In the context of the MTO/ETO manufacturing environments and supply chains, the modelled tasks should be in the context of the stages and activities in the MTO and ETO value chains, identified in Figure 2.2.

2.4. Conceptual thesis framework for the performance assessment model development

Exceedingly complex systems can no longer be decomposed for study, demanding the analysis of a system as a whole. These complex systems cannot be analysed under a reductionist approach, as the key interconnections and feedback loops impede keeping some elements constant to study others in isolation. Despite this, some degree of the systems decomposition is always necessary, as long as it still allows analysing a system as a whole (Glazner, 2009). For this, a framework for guiding the model building, using a simulation approach, for the MTO/ETO manufacturing environments is necessary. To comply with the requirements of complex manufacturing systems, it is important having a structured framework that guides the development of the simulation models and that can describe the behaviour and predict the performance of these systems and their supply chains. The proposed framework presented in Figure 2.5, is a structured approach to the development of simulation models for performance assessment and evaluation of the impact of improvement initiatives, inspired by the work of Dooley (2002) and Sargent (2013).

The framework for performance assessment in Figure 2.5 is divided into three stages: inputs, computational, and outputs. Each of these stages is sub-divided into different steps, among groups of tasks. The inputs stage is divided into three groups of tasks: the problem formalization, the model instances, and the static and dynamic domain understanding. This stage is responsible for providing all the information necessary for the development of the performance assessment models. It is during the problem formalisation stage that the target system to study is described, alongside the important performance determinants and system owned capabilities (which resources and capabilities are owned by the target system?), the target values or the Performance Determinants and Capabilities (PDC), and the mapping of the relevant performance indicators to be evaluated. All critical information about the system working principles should be collected for this task group. The static and dynamic domain understanding task group includes describing the system and its boundaries of analysis, defining the level of abstraction for the models developed and the time horizon for the analysis of the system, and defining the interactions that exist between the manufacturing system under analysis and the surrounding environment, e.g. the interactions that are established with other supply chain members. It is during the static and dynamic domain understanding that problems that can arise during the development of the simulation models should be analysed. These problems include establishing how the different business processes should be represented, for each company being modelled; synchronizing data exchange among the different supply chain members considered; establishing communication mechanisms for the interactions between information and material flows (Umeda and Zhang, 2006), and which are the relevant business processes to be included in the modelling exercise. This stage allows narrowing the scope of analysis of the model and focusing on the specific problem being analysed, while generally considering important interactions with elements that can be outside the scope of analysis, but that are still somehow influential. The model instances allow defining the model input data and generate the experimental design for the model execution. Whenever possible, this data should be observable and collected from the system being studied, through structured methods of data collection.

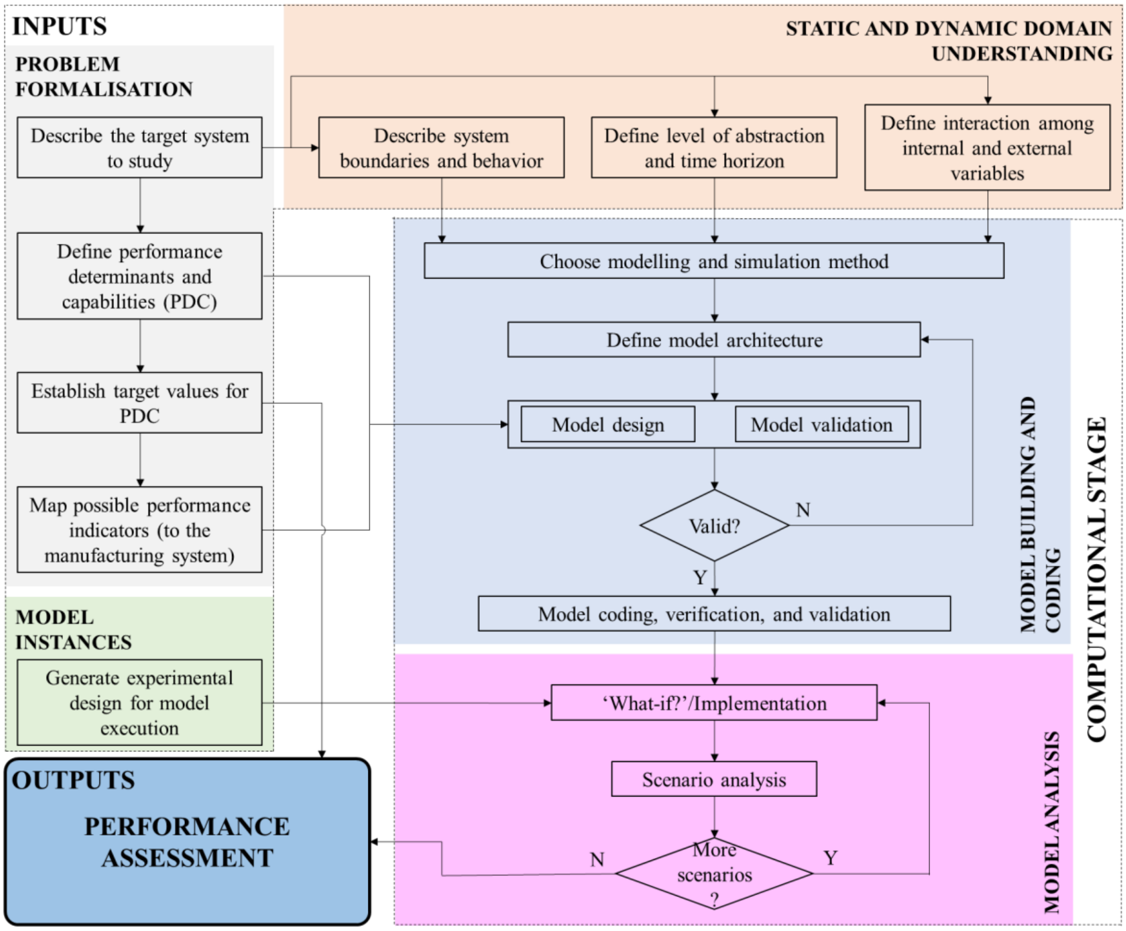


Figure 2. 5. Structure of the framework for performance assessment.

The computational stage encompasses two groups of tasks: the model building and coding and the model analysis. During the model building and coding, the modeler should select the appropriate modelling and simulation method(s) to be used. During this task, the modeler should find a good match between the business process to be modelled and the capabilities of the modelling and simulation methods. This will allow extracting the best features of the available methods, while maintaining the integrity in their use. This will be further addressed in Chapter 3 of this dissertation. After selecting the modelling and simulation method(s), the modeler must establish the formal model architecture, alongside specifying how the modelled business processes will communicate: When to pass information? Which information should be transmitted? To whom should the information be transmitted? The model can then be designed and validated for the design. The design of the model should consider the important performance determinants and the target performance indicators to be measured by the model. If the model design is valid for its purposes, the model can be coded and verified. The model verification is important to guarantee that the model follows the adequate working conditions, and the model validation after coding insures that the model is capable of reproducing conditions which are acceptable for the intended model application(s). The model analysis follows through implementing different scenarios based on the model instances. While scenarios are available to be explored, the model should run different input instances. When there are no more scenarios to analyse, the computational stage is finished.

The last stage of the proposed framework for performance assessment is the outputs. During this stage the results of the scenario analyses are compared with the target values for the system (using appropriate statistical methods), so that inferences about the system performance can be made. The performance assessment is made by comparing the measures obtained for the selected performance indicators, under the influence of the identified performance determinants, for the alternative scenarios explored.

Despite the framework in Figure 2.5 being represented as linear, it is an iterative framework, which can encompass multiple feedback loops. The fact that a modeler is standing on the computational stage, does not mean it cannot go back to the inputs stage to refine and challenge some of the assumptions made. For this, the framework should be seen as an iterative guiding tool, and not as a linear process for the model development. Additionally, this framework is generic, which means it does not specifically address the needs of the MTO/ETO supply chain, nor the full considerations needed to build models using different methods. A refinement to this framework is proposed in sub-sub-section 3.1.3. Roadmap for the development of hybrid MTO/ETO value chain models.

Chapter 3 – Research methodology and proposal for a Hierarchical and Hybrid Performance Assessment Model

Throughout this chapter, the scientific research method used in this work is explored, alongside the research design and the case studies considered in the scope of the thesis. The framework for the research design is presented, alongside a discussion about the most suitable simulation methods to represent the key MTO/ETO value chain activities.

3.1. The scientific approach

Every research process includes a set of logically ordered decisions that span from the problem formulation, through the design and execution of the study, and ending with the analysis and interpretation of the results (McGrath, 1981). In this research, the problem has been formulated throughout chapters 1 and 2. The present chapter focuses on the design and execution of the study. The scientific approach in this thesis uses quantitative modelling and computer simulation (Bertrand and Fransoo, 2002). Computer simulation corresponds to attempts in modelling a particular system or set of systems (McGrath, 1981), and it has been a key tool in aiding researchers in understanding complex systems. Research based on computer simulation is formal science, based on deductive rules (Swamidass, 1991). Though following a generally deductive and formal approach to the research design, in this work some form of induction and empiricism is used. This occurs for the generalizability of the use of the proposed modelling and simulation approach for MTO and ETO manufacturing environments (as in sub-section 3.3), and during the derivation of unobtainable data (type C data) (Robinson, 2004) for the studies presented in sub-section 3.2, through estimates and considering unobtainable data as experimental factors (e.g. product demand).

3.1.1. Simulation as a scientific method

Quantitative modelling as considered throughout this work encompasses building objective, though abstracted models that explain the behaviour (or part of it) of real-life operational processes, and capturing real-life decision-making problems faced by managers. The models are built considering causal relationships among variables, meaning that a change of value in one variable leads to a change in another variable, which is a function of the initially altered variable. For this, the models can be used not only to explain the current observations in the modelled process, but also to predict the future states of it (Bertrand and Fransoo, 2002). Simulation is an extremely powerful research tool that allows researchers to look at an artificial world moving forward into the future, giving an unprecedented opportunity to intervene and attempt to make improvements to performance (Dooley, 2002).

Harrison et al. (2007) considered simulation as a third way of doing science. It resembles deduction as the outcomes follow directly from the assumptions made, though avoiding the problem of analytic tractability; and it resembles induction as the relationships among variables can be inferred by analysing the output data, avoiding the problem of data availability, as simulation produces its own “virtual” data. Computer simulation is axiomatic research, in the sense that it produces knowledge about the behaviour of certain variables in the model and how to manipulate them, assuming a certain desired behaviour of other model variables (Bertrand and Fransoo, 2002). It is preferred when the case or problem is too complex to be solved through formal mathematical analysis (Bertrand and Fransoo, 2002, Harrison et al., 2007, Glazner, 2009). This type of research includes the study of highly relevant processes, but at the expense of obtaining lower scientific quality results (Bertrand and Fransoo, 2002).

Simulation models can be deterministic or stochastic. The deterministic models have no probabilistic elements and produce the same output each time they are run. The stochastic models have probabilistic components so the behaviour of the model in a particular instance depends from chance (Harrison et al., 2007). In this work, the models developed are stochastic.

Modelling and simulation are emerging key tools for the support of manufacturing in the 21st century. Simulation has been gaining relevance in the past few years, as it allows the systems designers to quantify and observe the behaviour of the systems, compare alternative designs, troubleshoot existing systems (Hosseinpour and Hajihosseini, 2009), and answering the question “What-if?” (Dooley, 2002). Dooley (2002) identified prediction and performance among the purposes for simulation. Simulation for prediction considers a model with a certain structure and governing rules and produces the output of the model. The output obtained upon using different structures and governing rules allows inferring what would happen in a real situation. It operates as a substitute for experimentation and intervention in the real system, especially when these are too dangerous, costly, untimely, or inconvenient. Simulation for performance can be used when there is an appropriately calibrated model. It can be used for tasks as diagnosis or decision-making, by mimicking uncertainty. Another key aspect of the simulation is gaining “insight” into the behaviour of complex systems, arising from their structure and governing rules (Glazner, 2009).

Following Dooley (2002), building a simulation model encompasses the following stages: conceptual design, code development, validation, experimental design, implementation, analysis, and interpretation.

- Conceptual design: The modeler determines what is to be modelled, which are the questions that need to be asked via the model, who will be using the model, and which are the model requirements. In this stage there are countless problems that can occur, including an insufficient explanation of the system behaviour at its boundaries, including too many rules in the model that make it difficult to test and validate (or exclude important elements), and assuming erroneously sequencing of activities. It is during this stage that the modeler must make choices about the simulation that make it more realistic to enhance its potential validity and generalizability.
- Code development: The computational model is implemented in a software code and tested to avoid errors. As referred by Sargent (2013), it is the verification of the computer model that ensures that the computer program of the model and its implementation are correct. It is the model debugging (Kleijnen, 1995).
- Validation: It is during the validation stage that the modeler assesses if the model derives in satisfactory results and insures a range of accuracy that is consistent with the intended application (Sargent, 2013). Several validation techniques can be used, including animation to graphically display the model behaviour through time; comparison to other models; data relationship correctness; degenerate tests, to assess if the model behaviour is tested by an appropriate selection of parameters; event validity, to assess if the events of the simulation model correspond to those of the real system; extreme condition testing; face validity, by asking individuals who possess knowledge about the system, if the behaviour is correct; historical data validation; internal validity, to assess the amount of internal stochastic variability of the model; multistage validation; operational graphics; parameter variability sensitivity analysis; predictive validation; structured walkthrough; trace; and turing test (Sargent, 2013). For the developed models, the validation techniques used were extreme condition test, partial face validity – individuals knowledgeable about the system were inquired about the model assumptions, but not the model output -, internal validity, operational graphics, parameter variability sensitivity analysis, structured walkthrough and trace.
- Experimental design: Requires the user to define a set of experiments, providing an indication for initial and run-time parameter values that will be used to determine answers to the questions posed. Experimental designs -full and fractional factorial – should be used as experimental design models.
- Implementation: Consists in executing the experimental design, including replicates (multiple-runs of a single experimental condition), but using a stream of random numbers. The transient behaviour of the simulation should be ignored (behaviour that is determined by the assumed starting conditions).
- Analysis: The model output replicates are averaged over an experimental condition, so that subsequent analysis is possible. Confidence intervals can be determined from the standard error of the replicates.
- Interpretation: Includes noting the observations from the analysis and results discussion.

The framework proposed in Figure 2.5 follows the above stages, but with a more iterative perspective. It is also important to build credibility in the model results (Kleijnen, 1995). The level of confidence in the model and its results determine the real value of the model. When a model is developed for a system that is not observable, it is not possible to obtain a high degree of confidence in the model. In these situations, the model output behaviour should be as thoroughly explored as possible (Sargent, 2013).

There are three schools of simulation (Dooley, 2002): Discrete Event Simulation (DES), SD, and Agent Based Simulation (ABS). DES is a hard positivistic method (Balaban et al., 2014) which involves the modelling of the organizational system as a set of entities that evolve over time, according to the availability of the resources and the triggering of events (Dooley, 2002). The entities flow through blocks of activities in the flowchart, stay in queues, are delayed, processed, seize and release resources, among others. Stochastic elements are usually involved (Borshchev and Filippov, 2004). SD is a post-positivist approach (Lättilä et al., 2010) that involves the identification of "key" state variables that define the behaviour of the system, and relating those variables to one another through differential equations (Dooley, 2002). SD models focus on the modelling of the behaviour of a system as a whole. These models are presented in diagrams of variables connected by arrows showing the directions of influence of the variables in one another (Harrison et al., 2007). The models are represented by stocks, flows between the stocks, and reinforcing and balancing feedback loops. SD abstracts from the single events and entities, focusing on the policies that govern the system, at a high abstraction level (Borshchev and Filippov, 2004). ABS is a positivist approach (Lättilä et al., 2010) which includes agents that attempt to maximize their utility functions by interacting with other agents and resources. The agent behaviour is determined by the embedded schema which is interpretive and action-oriented (Dooley, 2002). In agent-based models, the focus is on the behaviour of adaptive actions of those actors who make a social system and influence each other through their interactions. The behaviour of the system emerges from the interactions among agents (Harrison et al., 2007), and it follows a bottom-up modelling approach (Borshchev and Filippov, 2004).

As with any other approach, simulation encompasses multiple advantages and disadvantages. These are summarized in Table 3.1.

Models are used for supporting management decisions. The use of a single model will often be incapable of supporting all decisions (Fowler and Rose, 2004). In line with this, Dooley (2002) referred that the use of a single simulation method would be likely to change in the future, given the complexity of organizational systems that need elements from the three simulation schools, so their complexity can be appropriately captured. The following sub-sub sections explore the use of more than one simulation method to appropriately capture the manufacturing complexity and the evolution of the use of these approaches.

3.1.2. Hybrid simulation approaches

Simulation modelling arises as an appropriate alternative when the problem under analysis is complex (Borshchev and Filippov, 2004, Jahangirian et al., 2010) and time dynamics are important. Functions including factory floor models, warehouse logistics, R&D Project Management, and Manpower & Personnel are commonly addressed via simulation, yet with varying degrees of detail and at different abstraction levels (Borshchev and Filippov, 2004). For practical, real-world applications, especially when there is a growing need to address problems that cross the limits of a single enterprise function and in dealing with different layers of decision-making within a system, a simulation approach may be the only option (Jahangirian et al., 2010). However, a major concern arises upon deciding which modelling and simulation method best captures the intricacies, complexities, and connections of and within a manufacturing system.

Complex enterprises are often abstracted into subsystems to achieve a better insight into their working principles. Yet, this introduces major challenges when modelling enterprise wide solutions, because models used to simulate the individual behaviour of certain manufacturing functions cannot appropriately translate a complete manufacturing process (Glazner, 2009). It is the presence of manufacturing and non-manufacturing functions in the enterprise, the differences among the varied management levels, the frequency of the decision-making functions, and the multiple levels of detail that make a single method (standalone) simulation approach not to suffice the complex demands of modern businesses (Helal et al., 2007). A multidisciplinary approach, considering the use of more than one methodology and possibly combining those methodologies can become the only solution (Mingers, 1997). Indeed, Swinerd and

McNaught (2012) noted that the complexity of modern systems poses major challenges for single method simulation approaches, which boosted the growing trend in using hybrid simulation. Jahangirian et al. (2010), eight years ago noted that hybrid simulation was the third most used among the simulation approaches.

Table 3. 1. Advantages and disadvantages of a simulation approach

Advantages	
1. **Cost (Robinson, 2004)**	Experimenting with the real system can be costly, and the performance of the operation may worsen upon direct experimentation with the real system prior to simulation.
2. **Time compression (Robinson, 2004, Stefanovic et al., 2009, Fowler and Rose, 2004, Glazner, 2009)**	Simulation modelling allows obtaining results over a long-time frame and enables the exploration of new ideas in a shorter time.
3. **Control of experimental results (Robinson, 2004, Fowler and Rose, 2004)**	Enables controlling the conditions under which experiments are made, enabling direct comparisons.
4. **Experimenting with inexistent systems (Robinson, 2004)**	Enables experimentation, even when the real system does not yet exist.
5. **Modelling variability (Robinson, 2004)**	Simulation models can mimic the variability and model its effects.
6. **Restrictive assumptions (Robinson, 2004)**	Simulation models require few assumptions to be made, though the need to simplify the models require some assumptions to be made.
7. **Transparency (Robinson, 2004, Stefanovic et al., 2009) and repeatability (Fowler and Rose, 2004)**	Simulation is easier to understand, especially when an animated display of the model is created.
8. **Fostering creativity (Robinson, 2004)**	Ideas can be experimented in a risk-free environment.
9. **Creating knowledge and understanding (Robinson, 2004)**	It forces people to think about issues that would have otherwise remained unconsidered.
10. **Flexibility (Stefanovic et al., 2009, Glazner, 2009)**	Simulation models are easy to modify.
11. **Can be used for the analysis of complex systems (Stefanovic et al., 2009, Fowler and Rose, 2004, Dooley, 2002, Glazner, 2009)**	Simulation models allow capturing the real-world complexity, by addressing multiple interactions among sub-systems.
12. **Include real-world influences in the models (Stefanovic et al., 2009)**	It is possible to include influences, as the demand, that have real-world correspondence.
13. **Enable “What-if” analysis (Stefanovic et al., 2009)**	Simulation allows exploring complex systems under different scenarios.
14. **Scaling up (Fowler and Rose, 2004, Glazner, 2009)**	Scaling up of simulation models is only constrained by the available computational power.
15. **Ethical (Glazner, 2009)**	Allows experimenting without impact in the lives of those involved in the system under study.
Disadvantages	
1. **Computationally expensive (Robinson, 2004, Stefanovic et al., 2009)**	Developing the simulation model may encompass acquiring expensive software.
2. **Time consuming (Robinson, 2004, Stefanovic et al., 2009)**	Quality simulation models can be time consuming to develop and validate.
3. **Data hungry (Robinson, 2004)**	There is a significant need for data.
4. **Requires expertise (Robinson, 2004)**	Developing a simulation model requires skills in many dimensions, as conceptual modelling and use of software.
5. **Overconfidence (Robinson, 2004)**	There is the danger of considering everything to be correct without paying much attention to the model validity.
6. **. Does not guarantee optimal solutions (Stefanovic et al., 2009)**	Optimization of processes is not possible using only a simulation.
7. **Lack of model detail or excess detail (Harrison et al., 2007)**	There is the danger of including few/excessive information in the model.
8. **Programming errors (Harrison et al., 2007)**	Lack of appropriate model verification can lead to undiscovered errors.
9. **Poor translation of the formal model into the computer model (Harrison et al., 2007)**	Errors can be generated upon the model coding.

It is important at this point, establishing what is meant by hybrid simulation approach in the context of this work. The literature has been prone in identifying the struggle in establishing a definition and standardization of terms in the hybrid simulation realm (Balaban et al., 2014, Mustafee et al., 2017).

Swinerd and McNaught (2012) defined hybrid simulation approaches as "… *approaches which combine at least two of the three methodologies discussed.*", being the methodologies discussed SD, DES, and ABS. In broad terms, this is the definition adopted in this work. When trying to deepen definitions, and following the work by Mustafee et al. (2017), upon considering only the simulation part, we have developed what the authors call type C models that are multi-methodology, multi-technique hybrid simulation models. This is because the proposed models have been developed with continuous SD method and DES and ABS discrete methods. SD-DES and SD-ABS models are multi-methodology models, while DES-ABS models are multi-technique models. However, if we consider the conceptual modelling phase, all the stages prior to the model building and coding, and the model analysis stage, as in Figure 2.5, the developed models encompass elements of quantitative as well as qualitative nature. If these stages are to be considered, we are in fact using a type D model, which is a Hybrid Systems Model.

A hybrid simulation approach is often the only means to achieve a more natural and efficient solution. It is built on the premise that each simulation method has strengths and weakness upon modelling specific mechanisms and contexts (Glazner, 2009). While there is a wide range of problems that can be addressed through simulation modelling (Borshchev and Filippov, 2004), these problems are often addressed in isolation. In a hybrid solution, multiple models are employed that use different simulation methods and that are connected between them. Often the output of one model can be used as the input of another. Different areas of enterprise modelling have been using these hybrid approaches, including supply chains, production planning, and manufacturing decision-making. The diverse simulation methods are applied to the different areas considering their goodness of fit in representing the intended system behaviour (Glazner, 2009). Additionally, different designs for hybrid simulations can be considered (Swinerd and McNaught, 2012, Morgan et al., 2017, Barbosa and Azevedo, 2017). These include interfaced, sequential, enrichment, and integrated designs, as is explored in more detail in Paper B. An interfaced design considers that models from different methods are applied in an uncoupled fashion. Results from the model of each method are then compared to unveil opportunities of complementarity and compatibility. In the sequential design, the models from different methods operate separately, and the model from one method follows the other. The models are uncoupled, but dependent and complementary. In the enrichment design, a single method is used that adopts the principles from other method(s). Finally, in the integrated design, the models from the different methods are fully coupled, through a constant exchange of information and feedback mechanisms, in more than one point in time (Barbosa and Azevedo, 2017). General purposed modelling languages, as the Unified Modelling Language (UML) aid in the representation and communication of the different model designs.

Table 3.2 shows the results of a structured literature review (Barbosa and Azevedo, 2017) that tackles the use of hybrid simulation approaches in the manufacturing value-chain, targeting the classification of the hybrid models according to a taxonomy of designs of hybrid simulation, and highlighting the models focus areas, motivation for the use of a hybrid simulation approach, and relevant findings in the hybrid simulation literature. Additional works have been included that were not originally presented in the literature review in (Barbosa and Azevedo, 2017). These reflect more recent developments in the realm of hybrid simulation.

A total of 56 papers has been analysed and are presented in Table 3.2. Some observations are very immediate. There is a clear tendency of models towards an integrated hybrid simulation approach. This may show the attempts that different researchers have been making in establishing fully integrated designs towards the development of innovative simulation methods and solutions. The drive to develop hybrid simulations seems to vary a lot, according to the type of design being used. In the interfaced design, the aims of the authors encompass understanding which system variables are best represented by which methods (Crespo-Márquez et al., 1993, Ruiz Usano et al., 1996), understanding the methods capabilities (Van Dyke Parunak et al., 1998, Demirel, 2006), spotting complementarity opportunities (Johnson and Eberlein, 2002), and assessing the main differences among the simulation methods (Özgün and Barlas, 2009). The findings from the interfaced design have largely contributed to the literature, as these allowed a better understanding of the capabilities and range of operation of the different simulation methods. Interesting findings showed the great potential of SD for aggregate macro-modelling (Demirel, 2006) and centralized modelling (Van Dyke Parunak et al., 1998); while there were shortcomings in estimating detailed parameters of systems (Özgün and Barlas, 2009). DES was deemed appropriate for estimating factory performance (Crespo-Márquez et al., 1993) and for the detailed analysis of production lines (Ruiz Usano et al., 1996), with apparent shortcomings in the computational time and communication (Johnson and Eberlein, 2002). ABS was found to be most appropriate for environments in which discrete decisions were important (Van Dyke Parunak et al., 1998) and for capturing heterogeneity among the modelled members in a supply chain (Demirel, 2006). Works in the interfaced design seem to be earlier works, as the graphic in Figure 3.1(a) shows. The revised papers in the interfaced design appear until the year range 2005-2009, but not afterwards. Also, as the graphic in Figure 3.1(b) shows, publications classified as interfaced considered the SD-DES and SD-ABS combinations of methods.

In what concerns to the sequential design, the authors' intents seem to encompass complementing information derived from the model from one method, with information from the model of another method (Reiner, 2005), and overpassing some modelling inabilities of the simulation methods (Greasley, 2005). In the sequential approach, the authors either start by selecting one method for modelling the system and later realize the need to use another method for a better analysis (Rus et al., 1999, Greasley, 2005), or one of the methods is selected for building a model, whose outputs are used in a second model developed using another method (Abduaziz et al., 2015), encompassing feedback mechanisms, but never the simultaneous execution of the models of different methods. The use of the sequential design, as the graphic in Figure 3.1(a) shows, has been spread throughout the years analysed. Most of the publications under this design have focused on the SD-DES combination of methods, Figure 3.1(b).

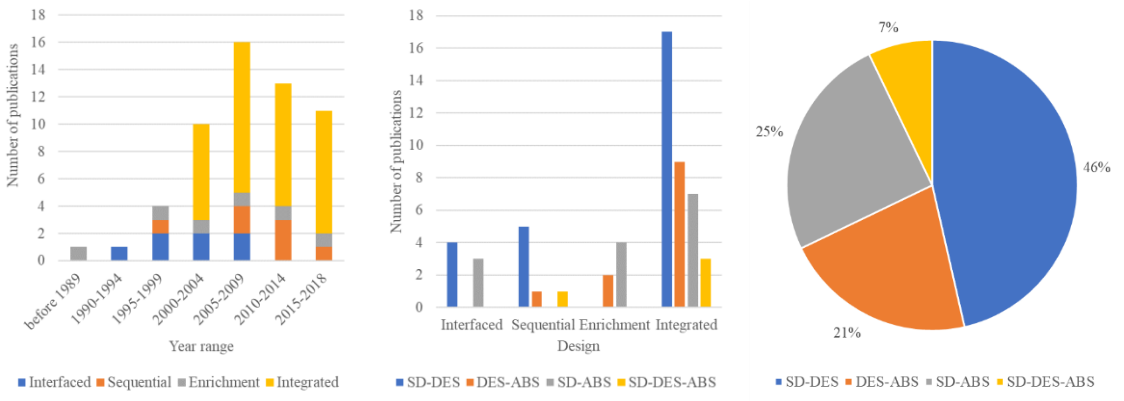
In the enrichment design, the use of the principles of one method into another method has mostly been accomplished by using a software that is typical for one method, but applying the principles (Renna, 2013, Osgood, 2007) or libraries from other simulation method (Pawlewski, 2015). There is always a dominant method in the enrichment design (Morgan et al., 2017). In this taxonomy, the target combination of methods has been among continuous and discrete methods, DES-ABS and SD-ABS, Figure 3.1(b), driven by the need to attribute intelligence to the resources or other decision-making actors in DES models (Renna, 2013, Pawlewski, 2015), or using array variables to emulate a multi-agent architecture (Kim and Juhn, 1997), that is so relevant in systems as supply chains, to account for the differences that exist among the interacting actors and opinions formed (Akkermans, 2001). The publications in the enrichment design have been spread throughout all the analysis years, as in Figure 3.1(a). The enrichment design has been key in developing solutions that complement single method approaches, giving it a wider range of applications and new capabilities that single methods cannot accomplish.

As noted earlier, most of the revised publications in the hybrid simulation realm focus on developing integrated approaches. Though fully integrated designs, that completely relax the methods boundaries and derive in new inseparable models (Morgan et al., 2017) may still need some development, it is under this design that the real meaning of hybridization becomes clearer. As the boundaries of the methods become more relaxed (while keeping the integrity of the methods), the dominance of the methods becomes less clear, and the final model equally reflects the features of the methods that have been used in its inception. The model cannot be executed without all the models from different methods being executed. Feedback among the models is constant. As Table 3.2 shows, using this design, among others, it is possible to achieve enterprise wide simulations, avoid unnatural use of the simulation methods, and establish flexible and adaptable supply chains during the model run time. Some models that have been classified under the integrated approach can be argued to belong to the enrichment design, particularly those developed using a DES-ABS combination, e.g. (Hao and Shen, 2008, Kukushkin et al., 2015). While these models do use agents in a DES model, it is a fact that the simulation software that the authors used was not dedicated to

DES, and that the relevance and contribution of the modules developed using DES and ABS was equal to the overall goal of the simulation. These are the reasons why these models have been classified under the integrated design. In the graphic from Figure 3.1(a), it is clear that the integrated designs appeared after the year 2000. This may be justified by the ever-increasing computational power that allows establishing more complex model architectures, and by the appearance of simulation tools, as Anylogic, that allow multi-method simulation, avoiding the need to couple models developed using different software. In the integrated design, most of the models have been developed by the combination of SD-DES methods.

From the literature review, and as Figure 3.1(c) shows, 46% of the revised publications, regardless the design in which these fit, have been developed using a combination of SD-DES. These are followed by the combination of SD-ABS, DES-ABS, and finally SD-DES-ABS. For this, most of the models focus on the combination of continuous and discrete simulation methods, indicating that clear gains can be achieved by these combinations, especially in hierarchical problem analysis. As SD and DES are methods that are much better established than ABS (Borshchev and Filippov, 2004), this may justify the clear tendency for developing models using these methods. Summarizing, the purpose of hybrid approaches is giving their users the possibility of using the best and most interesting features of each of the combined elements (Brito et al., 2011), while achieving a better insight into the complex and interdependent processes of very different nature (Borshchev and Filippov, 2004).

As the literature review shows, multiple interactions and model types can be built using a hybrid simulation approach. For this, it is important to establish a summary, as in Figure 3.2, of the analysed literature and target the most common relationships that are established among models from different methods. When the hybrid approach makes use of SD and DES, SD is always used at a higher abstraction level, modelling and simulating aggregate variables, while DES is applied for detailed models of manufacturing and services operations. This represents a highly hierarchical relationship established between the models. For hybrid SD-ABS models, the supply chain actors are often modelled as agents, whose internal processes and reaction mechanisms are modelled using SD; or ABS is used to give individual decision rules to SD models. Considering the close relationship established between the models from different methods, this a complementary relationship. Between ABS and DES models, the relations are often those between resources and operations. On one hand, ABS is used for modelling person's behaviour and human decision-making, or machine (other resources) behaviour; on the other hand, DES targets those operations in which people are involved. Approaches using the three modelling and simulation methods, e.g. Jain et al. (2013), use mixed types of relationships between the models of different methods – hierarchical, complementarity, and resources and operations.



(a) (b) (c)

Figure 3. 1. Distribution of the revised hybrid simulation papers. (a) Number of publications by year range and by design type; (b) Number of publications for the different designs, considering the combinations of methods; (c) Percentage of publications for the different combinations of methods.

Table 3. 2. Hybrid simulation models in the literature, considering the design taxonomy, the methods used, model focus area(s), the motivation for using hybrid simulation approaches, and findings for the hybrid simulation literature

Taxonomy	**Methods included**			**References**	**Focus area**	**Motivation for using hybrid simulation**	**Findings for hybrid simulation literature**
	SD	**DES**	**ABS**				
Interfaced	●	●		(Crespo-Márquez et al., 1993)	JIT/Kanban manufacturing process	Assess which features of the system are best modelled by each simulation method.	SD results followed the trends from DES models, showing the potential of SD as a solution for production problems. DES offered the best way to estimate factory features.
				(Ruiz Usano et al., 1996)	Production line with constant work in process control		SD and DES can be used in a complementary way, with SD providing an initial optimized estimation of parameters to be used in a thorough DES analysis.
				(Johnson and Eberlein, 2002)	Production plant and transportation system	Understand how SD tools can complement or replace existing DES tools and analysis techniques.	SD and DES can be complementary. While achieving poorer results, the SD approach ran much faster and engaged people in discussion.
				(Özgün and Barlas, 2009)	M/M/2 queuing system with crowd-dependent arrival rate	Assess under which conditions there were significant differences between SD and DES models.	SD and DES become closer under steady-state conditions, however SD is not appropriate for estimating queuing system parameters nor assessing precise statistical estimates of the system.
	●		●	(Van Dyke Parunak et al., 1998)	Supply networks	Assess the capabilities of the modelling methods.	ABS is most appropriate for cases in which there is a high degree of localization and distribution and where decisions are mostly discrete. SD is best for systems which can be modelled centrally and where dynamics are governed by physical laws and not information processing.
				(Scholl and Phelan, 2004)	Long-term firm performance	Use of dynamic modelling for theory integration efforts.	Models built in a bottom-up (ABS) and top-down (SD) fashion can be modified using insights from the other model to achieve higher confidence in the model output.
				(Demirel, 2006)	Supply chain	Assess the capabilities of the modelling methods.	Macro modelling using SD can capture the supply chain dynamics but misses the heterogeneity among the individual supply chain members.
Sequential	●	●		(Rus et al., 1999)	Software project planning and management	The use of DES arises as a need to complement developed SD models.	While the SD model can be used for project planning, predicting the effect of management and engineering decisions, and as a training tool; the DES model is used for more detailed project tracking and control.
				(Greasley, 2005)	Production-planning in a manufacturing plant	The use of SD resulted from the inability of DES in modelling the problem of delivery performance.	DES provides quality results upon investigating the effect of changes in production sequencing rules, but must be complemented by an SD approach to assess factors with impact in the organizational context.

				(Reiner, 2005)	Supply chain performance management	Complementing information derived from the DES model with SD models.	DES models can be used for estimating supply chain operational measures, while SD models can use as input values obtained from the DES model to assess the impact of changes in these variables in the customer satisfaction, loyalty, and financial indicators.
				(Jamalnia and Feili, 2013)	Aggregate production planning	DES are limited to the detailed analysis at the operational level, while the SD models can address qualitative issues and are more suitable for decision making at aggregate levels.	DES best captures operational level, shop-floor activities included in the aggregate production plan; the output of the DES model can be used as input for the SD model, which best captures strategic decisions.
				(Abduaziz et al., 2015)	Green logistics assessment	DES models must be used for the detailed representation of processes for which improvement is possible.	SD appropriately represents the logistical activities within an assembly line at a high level, while DES models are used for the detailed representation of improvement opportunities.
		●	●	(Vasudevan and Son, 2011)	Evacuation safety and productivity in a manufacturing facility	ABS is the best to represent human behaviour and the DES models best estimate the productivity of the manufacturing system.	The agent model appropriately captures each person's actions and interactions with others, while the DES models appropriately capture details of productivity assessment in manufacturing.
	●	●	●	(Jain et al., 2013)	Energy consumption in the supply chain	Top-down modelling of the system is considered, which starts from an aggregated modelling perspective and detailed modelling when opportunities for improvement are identified.	The supply chain is well captured at an aggregate level by an SD model, but certain processes that can be improved are best explored by a more detailed representation using DES and/or ABS.
Enrichment		●	●	(Renna, 2013)	Job shop management	The use of a multi-agent architecture allows the integration of additional features in the DES model.	Adding the multi-agent architecture to the DES simulation provides a very dynamic simulation environment.
				(Pawlewski, 2015)	Warehouse operations in a supply chain	The DES process approach is insufficient for dealing with the flow of entities, and the operators must be seen as tasks' executers with decision capabilities.	The ABS approach enriches the DES by giving a defined behaviour to the agents that have decision-making capabilities. This would be unfeasible with the sole use of DES.
	●		●	(Wolstenholme and Coyle, 1980)	Coal mine operations	Need to incorporate random discrete events in the bunker control policy.	The modelling problem became simpler by incorporating the equations that reflect discrete and random events.
				(Kim and Juhn, 1997)	Market price system	The array variables in SD can be used to incorporate lots of similar agents.	SD modelling platforms can be used for multi-agent systems, as SD models containing array variables allow simplifying the causal structure of complex interactions of multi-agent systems.
				(Akkermans, 2001)	Supply networks	It is more straightforward modelling individual behaviour by using agent-based principles in an SD environment.	It is advantageous incorporating ABS models in an SD environment because actors have individual mental models about the other interacting supply chain actors.
				(Osgood, 2007)	Generic	Modelers using aggregate SD approaches should weight the possibility making models deeper and the opposite for ABS modelers. SD tools would	Tools for ABS and SD should converge to provide more quality for modelers. Modelers would also benefit from tools

					benefit from incorporating discrete rules and ABS from a consistent mathematical framework.	encompassing different levels of model aggregation, and multiple levels of model abstraction.
Integrated	●	●	(Rabelo et al., 2003, Rabelo et al., 2005, Helal and Rabelo, 2004)	Enterprise simulation	DES models developed for production decisions do not capture the impact of those decisions in the whole enterprise. An SD approach is necessary for that.	Integrating SD and DES is valuable for enterprise simulations, as multiple space and time resolutions can be achieved. Hierarchical aspects of the enterprise can be captured.
			(Venkateswaran and Son, 2004, Venkateswaran et al., 2004, Venkateswaran and Son, 2005)	Hierarchical Production Planning	DES models best capture analysis at the operational level, while SD models are better at representing the dynamic flows of managerial, high level decisions.	SD and DES models complement each other, allowing achieving better solutions. The use of both models allows representing the system under different perspectives and integrating multiple feedback loops.
			(Helal et al., 2007, Rabelo et al., 2015, Pastrana et al., 2010)	Manufacturing enterprise	SD has a strong background in modelling aggregate level decision-making, while DES is widely acknowledged for good performance at the detailed operational level.	The simulation methods, SD and DES, maintain their integrity in the proposed hybrid SDDES method; a formalism for the integration of the methods is proposed.
			(Rabelo et al., 2007)	Value chain analysis	SD can well capture the extended enterprise system, while DES can model the manufacturing and service sub-systems.	The use of SD in combination with DES allows reducing the detailed statistical analysis of DES models. SD can well estimate demand for products and services, quality levels, customer reactions, investment decisions, and product and service development functions. The results can be used as input to a DES model to study the performance of the manufacturing and service facilities.
			(Umeda, 2007, Umeda and Zhang, 2008, Umeda and Fang, 2009, Umeda and Zhang, 2010)	Supply chain	SD can represent feedback mechanisms, while DES can assess the systems' performance.	SD models can be used for representing the external management environment, including marketing, logistics and plant engineering issues, while DES models can represent manufacturing, inspections, shipping, transportation, and planning.
			(Jacob et al., 2010)	Market	The analysis of business systems with time-discrete and time-continuous components is not suitable for SD and DES used in isolation.	The authors proposed an approach for controlling time-discrete and time-continuous behaviour upon integrating SD and DES, to avoid redundancy and consistency problems.
			(Jovanoski et al., 2012)	Enterprise simulation	DES models have shortcomings when it comes to modelling the entire enterprise. These can be complemented by using an SD approach	The use of a hybrid simulation approach avoids using the simulation methods in an unnatural way, avoids the increased complexity upon attempting to model the entire enterprise using a single approach
			(Albrecht et al., 2014)	Planning and optimization of production systems	DES shows great benefits in modelling the detail complexity of the production system but falls short in representing strategic thinking. This is complemented by the use of SD.	SD and DES share the same conceptual model of a production system, which allows evaluating measures at the operational level and evaluating the future dynamic structural behaviour.

		●	●	(Maione and Naso, 2004)	Agile manufacturing	There is the need to include agents and their redefining states as inputs to DES formalism models.	The multi-agent architecture can continuously adapt the decision logic over time as a result of the natural evolution of the simulation of the environment. Each agent was modelled as an atomic discrete event system.
				(Hao and Shen, 2008)	Kanban-based material handling system	Agents add intelligence to a DES model.	ABS greatly improves the performance of the material handling system by considering intelligence, controllability and adaptiveness. This allows simulating diverse dynamic situations and achieve more detailed information.
				(Wang et al., 2013a)	Virtual organization	Actors in ABS are modelled in close proximity to agents in the real-world, in a decentralized way. DES models are built in a centralized way and can benefit from the movement of entities and resources, modelled as agents.	The authors proposed a message bus based on Java message services to improve the results of hybrid models that are typically obtained with of the shelf software tools that allow the building of hybrid models.
				(Borucki et al., 2014)	Delivery process in the automotive industry	DES has been used for modelling manufacturing and logistics systems. ABS can complement DES by giving the transport agents an incorporated behaviour and interaction with other agents.	The mixing of DES and ABS improves the representation of product delivery methods
				(Khedri Liraviasl et al., 2015)	Reconfigurable manufacturing systems	ABS is suitable for modelling systems in which there are autonomous agents that deal with frequent changes – this is the micro-level modelling. DES can be used for the macro-level modelling, for the performance assessment of the production performance.	The use of ABS allows considering agents which are very different in nature, through the use of different coding for the conditions analysis. DES was very useful for process modelling and operations sequencing.
				(Kukushkin et al., 2015)	Packaging lines	DES can be used for simulating the processes at the production line, while ABS can be used for implementing the machine behaviour logic.	A simple model can be implemented integrating both simulation methods that are an aid in finding optimal production strategies.
				(Sadeghi et al., 2016)	Semiconductor manufacturing	The different simulation methods are selected based on the system to be modelled. It can be difficult and time-consuming developing models using a single simulation method.	ABS is a flexible method that allows building an adaptive structure. However, it does not consider the queuing concept, which is naturally modelled using DES. DES can be used for complementing an ABS approach.
				(Lieder et al., 2017)	Circular economy	Need to map individual product components' states with relevant design decisions and data and modelling the closed-loop supply chain.	The use of DES and ABS allows connecting the design at the component level with the business strategy.
				(Nagadi et al., 2018)	Smart manufacturing systems	ABS allows including inherent behaviour to resources in a DES model.	Resources as machines can be considered autonomous agents that can be part of a DES model.
	●		●	(Schieritz and Größler, 2003, Größler et al., 2003)	Supply chain management	The integration of the methods can serve for reducing the complexity of the models.	The structure of a supply chain in the SD model is predetermined before the simulation and is static during the simulation run. By incorporating ABS the supply chain structure, it can become

							adaptable during the simulation run and is not upfront determined.
				(Martinez-Moyano et al., 2007)	Financial stability	ABS and SD can both be used for representing complex systems, but with different levels of aggregation and reasoning.	Hybrid simulation approaches improve understanding and insight into complex phenomena, through combining models with different levels of aggregation.
				(Duggan, 2008)	Beer game	SD and ABS approaches can provide good and complementary insights into complex problems.	SD-ABS models can be used for the test of different heuristics to assess the best available alternatives.
				(Kieckhäfer et al., 2009)	Product strategy decisions	SD can be used for modelling market regulatory conditions and ABS can model individual decision rules.	A modular simulation environment including the use of SD and ABS allows analysing different portfolio decisions.
				(Asif et al., 2016)	Supply chain	Need to capture internal feedback in the systems and complex interactions among consumer behaviour and social dynamics.	Hybrid approaches allow modelling mutual interactions among critical business factors, product design and supply chain.
				(Tan et al., 2017)	Supply chain	SD allows a broad view of the supply chain, while ABS gives a more detailed perspective.	The target company was represented by an agent-based model, while the whole supply chain was simulated using an SD model. The authors argued that this would be desirable given the unavailability of data for all SC members, to allow the full modelling considering an ABS approach.
	●	●	●	(Wang et al., 2013b)	Automotive supply chain	The different modelling and simulation methods have been widely used in the literature at the supply chain level, even if for different purposes.	DES is used for simulating the assembly process, SD for the high-level production model, and ABS for simulating the different agents in the supply chain and functional agents in the core enterprise.
				(Wang et al., 2014)	Life cycle assessment	The integration of the different simulation methods allows simulating short and long-term performance under varied scenarios. The advantages of the methods can be combined.	SD can be used for modelling the workflow and calculating the energy consumption. DES models are good for the detailed work processing, and ABS for creating connections with the consumer behaviour.
				(Barbosa and Azevedo, 2018b)	Internal MTO/ETO supply chain performance assessment	MTO/ETO companies have to cope with processes which are very different in nature, e.g. the product development and the production, assembly, testing. Given the availability of information about these functions, and the intended level of model detail, a need to use a hybrid simulation arises.	The complex MTO/ETO manufacturing internal value chains can be successfully modelled and simulated using a hybrid approach. Product development functions can be simulated using an SD approach, while the product realization can be simulated using DES. As the variety of products in these value chains is high, the products can be modelled as agents, as well as the knowledge resources.
				(Barbosa and Azevedo, 2018a)	MTO/ETO supply chain performance assessment	The complex MTO/ETO supply chains include processes which are better captured by different modelling and simulation methods, given their varied dynamics, time horizon, detail, and available information.	The external MTO/ETO supply chain is better represented by an ABS approach, with each value chain node being represented by an agent; product development is better represented by an SD approach, and the product realization by a DES approach. Support functions insure the communication between models.

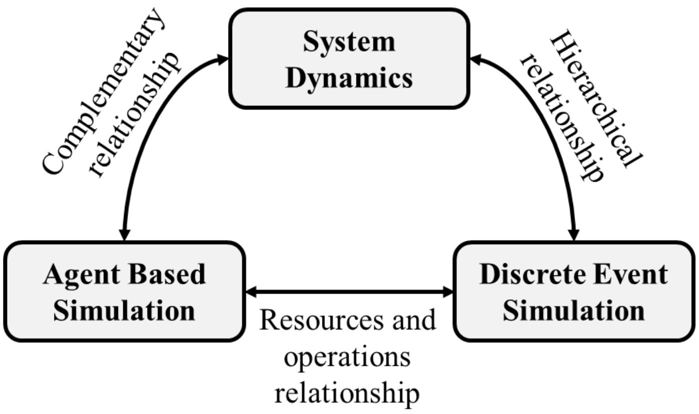


Figure 3. 2. Types of relationships established between models from different methods, considering the hybrid simulation literature.

DES has been often used for modelling enterprise behaviour. DES is easy to understand from theoretical and practical perspectives given the simplicity and the ease in representing models through a UML language. Those who are familiar with the system can easily understand how the model operates. It has been highly used for the analysis of process performance, identification of bottlenecks, and retrieval of key system statistics, as the servicing time, or process throughput. However, these models cannot represent business processes that do not encompass an entity flowing through a path. Examples of such systems include strategic management and knowledge management. DES models are computationally intensive for large processes, which can be more efficiently captured through a continuous equation approach. The entities in DES are passive, which means these do not make decisions, adapt, or learn. The core focus of DES is process modelling, and it is likely that it remains the preferred method for that purpose (Glazner, 2009). DES is a suitable approach when problems encompass variables that change in discrete times and by discrete steps (Özgün and Barlas, 2009). Models built using DES are very flexible and capture complex interactions among entities and detailed features of the modelled system (Heath et al., 2011, Brito et al., 2011). This method is not exempt from drawbacks, among which stand out the high data requirements, and being time consuming to develop and run (Heath et al., 2011).

On an opposite position, SD is strong in modelling the enterprise at a higher decision level. It is effective in capturing a broad perspective of the system. SD simulations run very quickly, and their structure makes easier the identification of the key model variables and the policy options that can be used to control the system behaviour (Glazner, 2009). SD is a useful approach when there is the need to model processes without knowing much about the micro-level processes (Mustafee et al., 2017). Despite these advantages, SD models only work in aggregate terms, which makes modelling the heterogeneity a challenge (Glazner, 2009, Heath et al., 2011). Yet this aggregation enables implementing simple models of a high-level structure of a system. While the aggregated data collection can be challenging (Glazner, 2009), data requirements are not so demanding in SD (Heath et al., 2011). It may be difficult to capture quantitative relationships among variables (Glazner, 2009).

ABS allows modelling of heterogeneous populations. It is possible to model bottom-up behaviours and consider more realistic assumptions about the models. This method can model a great multitude of problems in varying contexts. Behaviour adaptation is possible for agents. However, the behaviour of the models can be very difficult to validate and verify. These models can become very complicated and computationally intensive. ABS cannot model in a top-down fashion, which is prohibitive for some enterprise modelling functions. Most manufacturing processes could be modelled using an ABS approach, but this would require an additional effort without the added benefits (Glazner, 2009).

Model hybridization has increased with the high availability of simulation packages that help in developing hybrid simulation models (Mustafee et al., 2017). Having appeared as a consequence of the limitations and biases that standalone simulation methods have in capturing the holistic dynamics of all functions in an enterprise (Glazner, 2009), hybrid simulation approaches have many purposes that are not fulfilled by standalone simulation. These include the complementarity of the methods, exploring multilateral problems, data availability and usability, and exploration of a unique representation of systems (Balaban et al., 2014). The advantages of hybrid simulation include enhanced flexibility, adopting a problem-oriented approach, adopting high levels of detail only in required functions, establishing trade-offs between accuracy of the results and the simulation performance, overcoming the limitations imposed by the use of a single method, tackling the complex problems imposed by the modern systems (Mustafee et al., 2017), extracting the best features of each simulation method (Brito et al., 2011), and overcoming problems of model consistency, redundancy of components and model investigation effort (Jacob et al., 2010).

Despite these advantages, the use of hybrid simulation approaches must be well justified. It can be extremely challenging reasoning the selection of the methods that most appropriately capture the representation of certain functions (Balaban et al., 2014) and the represented models must be of equal importance to the overall goal of the simulation model (Jovanoski et al., 2012). Furthermore, combining models from different methods requires a lot of effort and precision upon establishing how often and when information is to be shared among the models (Martinez-Moyano et al., 2007); a good deal of attention must be paid to the conversion of the time units to insure proper data exchange (Martinez-Moyano et al., 2007, Martin and Raffo, 2000, Mustafee et al., 2017); and good knowledge about the different methods is required to find a good fit between the models (Mingers, 1997).

As referred by Owen (2013), the selection of the modelling approach must consider the needs of the problem that is being analysed. Additionally, as the use of hybrid simulation approaches must be well justified, we argue that the problem at hand, modelling the MTO/ETO value chain, does encompass processes of very different nature, and actors that may need to be modelled with varied degrees of detail. Furthermore, while some of the key processes in the MTO/ETO supply chain, as the product design, are highly uncertain, have very few information upfront, and encompass multiple feedback mechanisms; others, as the production and assembly of standard MTO products are well-known and established. For this, a unique and innovative solution that targets different levels of detail, data aggregation and availability is critical for the study of these complex value chains.

It is important to define a comprehensive framework for the development of the hybrid conceptual models and for their implementation (Eldabi et al., 2016). Some frameworks have already been proposed in the literature and will be the basis for the refinement of the framework in Figure 2.5, to capture the inherent features of the development of hybrid simulation models for the MTO/ETO value chain.

3.1.3. Roadmap for the development of hybrid MTO/ETO value chain models

The framework presented in Figure 2.5 is a generic framework that could be used for the development of any type of simulation, regardless the target system. For this, it is imperative to refine the framework for its application to the MTO/ETO context. Furthermore, the framework must also contemplate the possibility of developing models using more than one simulation method. Considering this, it is also important to establish the relevant model inputs, outputs, and highlight the simulation methods that can be used for the different parts of the system and address how to establish the appropriate information transfer mechanisms and synchronization among the models from different methods.

Several frameworks have been proposed in the literature for the development of conceptual models for simulation or for conducting hybrid simulation modelling. Robinson (2004) proposed a conceptual modelling framework consisting of four key elements, including developing the understanding of the problem, determining the modelling objectives, designing the conceptual model, including the inputs and outputs, and designing the content of the conceptual model. This framework starts from the problem and the modelling objectives to determine the experimental factors (model inputs), the simulation model and achieving the responses (model outputs), which must determine the success in the achievement of the modelling objectives. Lorenz and Jost (2006) developed an orientation framework for multi-paradigm (hybrid simulation) modelling. The authors propose that a modelling framework for hybrid simulation must consider three key elements: purpose (why?), object (what?), and methodology (how?). Helal et al. (2007) proposed a framework for the integration and synchronization of DES and SD for applications in manufacturing systems, based on a modular view of the system. Lynch et al. (2014) proposed a framework for conducting multi-paradigm (hybrid) modelling. Their framework is divided in three parts, the reference modelling, conceptual modelling, and simulation building. Each part is divided into multiple stages. During the reference modelling, the authors propose that the problem situation is explored, alongside the documenting of facts and assumptions, categorization of statements, and check for completeness. In the conceptual modelling, the authors propose the design of the implementation-independent architecture, the formulation of the modelling question, assessing the need for multi-paradigm modelling, identifying the appropriate paradigm per statement, deciding the simulation platform, designing the implementation-dependent architecture, and checking for consistency. Finally, the simulation building included the simulator selection, and the simulation building. Feedback among the framework stages was considered. The authors identified different selection criteria for model hybridization. Other frameworks for hybrid simulation in the healthcare industry have been proposed in the literature (Eldabi et al., 2016), which are not explored in the context of this thesis.

The above example frameworks show that a great deal of attention has been devoted to the technical challenges that are imposed by using hybrid simulation approaches. Most technical concerns encompass justifying the need of a hybrid approach, selecting the appropriate methods to target the different parts of the system, the synchronization, and information transfer among the models from different methods. Despite valuable, the proposed frameworks in the literature do not focus on the MTO/ETO value chain representation nor focus on the relevant stage of decomposing the problem, to make it manageable. Additionally, there has not been an effort in building hybrid modelling and simulation frameworks considering previous work. This enhances the problematic of the spread of information and inconsistent literature nomenclature. In our approach, we intend to overcome these gaps, by focusing on a framework for the MTO/ETO supply chain, through a system decomposition frame and building on the existing literature to refine the initial framework designed in Figure 2.5.

Following the framework designed in Figure 2.5, the inputs stage encompasses all tasks that relate to the identification of the problem, defining the model instances and limiting the boundaries of the model to be developed. The target system to study in the context of this thesis is the MTO/ETO value chain – both internally driven for a focal manufacturer - and at the external level – considering upstream and downstream interactions with customers and suppliers. The relevant performance determinants and performance indicators have been identified, respectively, in sub-section 2.3. Performance determinants in MTO and ETO, and in sub-sub-section 2.2.4. Performance indicators. Following the mapping of the stages and activities in the MTO and ETO value chains, in Figure 2.2, and the complexity drivers in these chains – suppliers, manufacturers, and customers – it is possible to understand that the problem at hand is very big and encompasses activities that are very different in nature and act at different decision levels. Therefore, describing the system boundaries and behaviour, the level of abstraction and time horizon, and defining the interactions among internal and external variables is a challenge. Following Helal et al. (2007) and Glazner (2009), some degree of system decomposition is necessary, and a modular approach is used to make the problem manageable.

Magee and de Weck (2004) proposed a classification for technical systems considering their degree of complexity: I – part, component; II – group, mechanism, sub-assembly; III – machine, apparatus, device; IV – plant, equipment, complex machine unit. For the decomposition of the MTO/ETO value chain, we use a similar approach, based on the complexity of the elements being modelled. We consider four levels of complexity of the system modules, and each entity in the levels is a singular, identifiable, separable element, that exists by itself, whether inside other entities or in isolation. The degree of complexity is based on the number of functions that each module encompasses, and the other modules it integrates. The four levels considered, by decreasing order of complexity are value chain node, human or composed artefact, target acquisition, and target acquisition part. Figure 3.3 shows the MTO/ETO value chain decomposition.

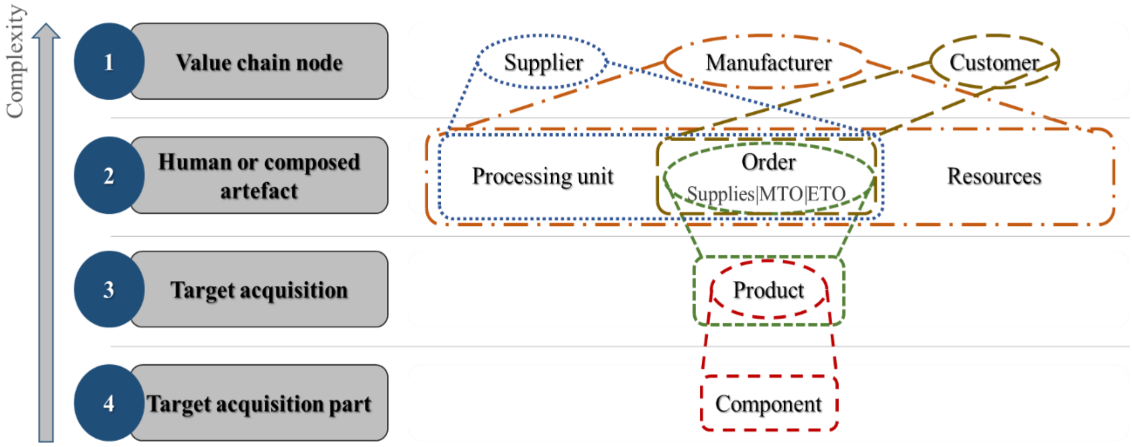


Figure 3. 3. MTO/ETO system decomposition for modelling and simulation purposes.

The value chain node level represents those entities among which information and/or products are exchanged. These are the most complex entities as several coordination functions and other less complex entities are included in their internal structure. The human or composed artefact level entails entities that are implicitly included in the value chain nodes and/or are exchanged among these. At this level are included entities that are key for the development of the functions and activities within the value chain node. The human or composed artefact level includes the orders that are exchanged among customers and the manufacturer, and among the manufacturer and the suppliers (suppliers of raw materials, standard components, and special components); the human, machine or transport resources that are involved in the completion of the orders, and the systems that are involved in the production, assembly, testing, delivery, and commissioning of the products (processing units). The level that follows is the target acquisition. This level includes the products that are the final goal of the orders. The products can be those parts/components that are ordered to the suppliers, or the MTO or ETO end-products, that are ordered by the customers. The final level in the complexity hierarchy included in the system decomposition is the target acquisition part. These are the components that make the MTO and ETO products and represent the least complex entities in the modelled system.

The support activities are not explicitly represented in the system decomposition, as these are not existing *per se*, but arise as a need to coordinate the entities. These activities exist in the manufacturer entity. The same applies to the tendering primary activities. In what concerns to the product development primary activities, these are specified and exist inside each order.

The decomposition of the MTO/ETO system as in Figure 3.3 allows establishing the boundaries for the modelling and simulation exercise. Each of the modules originated by the system decomposition contains the primary and support activities identified in the stages and activities of the MTO/ETO value chain in Figure 2.2. As expected, there may be different levels of information regarding each value chain node.

Hence, the fact that these stand at the same system decomposition level, does not mean that these integrate the same amount of information, nor level of detail. The manufacturer, which is the focal company in the modelling exercise, is the value chain node that encompasses the higher complexity and entails more of the primary and support activities. This node is responsible for coordination with suppliers and with the customers.

After understanding that a hybrid simulation approach is the appropriate to tackle the problem at hand, a number of considerations must be made. Upon designing a hybrid simulation model, the selection of the most appropriate methods for each modelled function is one of the most challenging tasks, and there are no defined guidelines on how to select the most appropriate methods (Balaban et al., 2014). To develop a good hybrid model it is key to establish the differences in how each modelling method represents the desired functions (Rus et al., 1999), and understanding that information exchange among models of different methods should only occur when meaningful changes in the system have occurred (Swinerd and McNaught, 2012). This is obviously a function of how each modelling method represents time (Swinerd and McNaught, 2012, Mustafee et al., 2017). In this line, we follow the framework proposed by Lorenz and Jost (2006), and agree that to establish the appropriate simulation approach, it is important to answer the three key questions: Why? What? How?

The representation of the MTO/ETO value chain can be appropriately achieved through an agent-based approach, though other simulation approaches, as SD, could have been considered. Indeed, the three simulation methods could present features that make them fit for representing the supply chains. Despite this, the SD supply chain representation considers aggregate and strategic modelling approaches (Tan et al., 2017), and a static model structure (Schieritz and Größler, 2003), which do not well represent the varied features that are possible for the supply chain nodes. Also, despite having been successfully applied to relevant functions at the supply chain level (e.g. logistics) (Borucki et al., 2014), the DES approach is data hungry and would not lead to a natural representation of the varied features and functions of the embodied value chain nodes.

Agent-based approaches can effectively be used to simulate supply chains in which each business unit is an agent that interacts with the other business units and with the environment through discrete events. Despite this, it is important to retain that there may be different levels of visibility and information for the different business units, which hinders the detailed modelling of all the behaviours in the supply chain (Tan et al., 2017). Keeping this in mind, it is put up front that the modelling in this work considers the general structure for an agent-based approach but seeing that the simulated behaviour of the agents is constrained by the levels of information available and by their role in the value chain. Indeed, the entities identified in the MTO/ETO system decomposition in Figure 3.3, except for the production unit, have been considered as agents. For this, a great multitude of agent types exists in the global model, which pushes to establish an appropriate definition for an agent. The work of Abar et al. (2017) is considered for this purpose. The authors defined an agent as *"…an entity, notion or software abstraction similar to the well-known programming specifications such as objects, methods, procedures and functions… presents a distinctly higher scale software abstraction that defines a complex software unit… is primarily typified in terms of its intended actions… inherently intuitive; it possesses the ability to perceive and respond to the changes within the surrounding domain… having sophisticated intellectual capabilities such as reasoning, learning and planning, thereby incorporating the resource knowledge of the underlying problem domain."*.

In the system decomposition proposed, the agents at the lower complexity levels, the components and the products, are simply passive entities that are transformed during the product development and manufacturing activities. These have been specified as agents to account for the varied product features that exist and the product development and manufacturing requirements they have. As for the higher order complexity agents, these include intrinsic behaviour that is modelled according to specified needs and have the capacity to reason about the surrounding environment and their own needs. Orders have been considered as individual agents because multiple orders with different features, and levels of completeness can co-exist inside the manufacturer agent. Resources, particularly transport and human resources have also been considered as agents because their individual states in practice influence the completeness or delivery of the orders. The production unit, though not being an agent itself, is an integral part of the behaviour of the supply chain nodes and determines important system performance measures at the shop floor level. Also, the production units represent processes that all target acquisition and target acquisition parts must undergo to achieve the fulfilment of the orders.

Having established that the hybrid simulation models for the MTO/ETO value chain are specified based on an ABS approach, it is important to address the modelling issues for the primary and support activities in the value chain. Considering this, the following discussion specifies, for each primary and support activity the Why? What? How? questions, the agents in which these are included, the input and output information, and the methods to establish interactions with other system models. The interaction between the models from different methods can be established through shared variables or events that exist across the models; for this, the outputs from one model can inform a model from other method (Glazner, 2009).

Tender

Why? As explored in the literature review section, tendering is a relevant activity in the MTO/ETO supply chain, whose goal is to start a soliciting process for the products. Tendering can occur both for the final ETO products and start by the action of the end customer; or for special components that must be outsourced and start by the action of the manufacturer.

What? The start of a tender is an event that occurs in the system in response to a need of a supply chain node. The information contained in the tender is uncertain, and different for every tender proposal.

How? The tender is represented and executed by a discrete event in time.

Agents. The request for tender can be initiated by the customer or by the manufacturer, therefore these two agent types include the tender request function.

Input and output information. Upon initiated by the customer, the tender request must contain information about the products. First and foremost, the tender request must specify if it is an MTO or ETO product. The tender request originates a new order agent, that must contain information about the performance determinants. The information must be retrieved from a database, considering that the demand information is a model input. When initiated by the manufacturer, the tender request originates a new component agent, that must contain information about the complexity determinant of the component being ordered.

Interaction. The event trigger is the responsible for the interactions among agents and variables specifying the products or/components (e.g. product type, lead time, component complexity) are shared.

Quotation

Why? Quotation is another key primary activity in the MTO/ETO supply chain, whose purpose is to reply to a tender request, with an estimated cost and time for supplying the products and/or components.

What? The quotation response is an event that starts in the order system for ETO products when the initial design of the product is finished, and initial planning accomplished; and for MTO products when customization is finished, and production planning estimated. In the supplier system is an event that starts when the cost and delivery time for the special components are estimated.

How? The quotation is represented and executed by a discrete event in time.

Agents. The quotation reply is initiated inside the order agent. When the product development/customization activities and cost estimation are finished, for MTO and ETO products, or when the cost and delivery time for special components have been estimated, an event is triggered inside the order, signalling to the manufacturer or the supplier that a response is ready.

Input and output information. The input information for the quotation is the signalling of the end of the product development/customization and cost estimation. As an output, the quotation informs about estimated cost and delivery time.

Interaction. The event trigger is the responsible for the interactions among agents, and the expected costs and delivery date are the shared variables among the manufacturer and customer, or supplier and customer.

Procurement

Why? In the context of the developed model, the procurement corresponds to finding the suppliers for the special components. It is a critical activity for the MTO/ETO supply chains.

What? The procurement function is initiated when a tender request for ETO products enters the manufacturer.

How? The procurement is not explicitly modelled and considered only at the tendering stage. To simulate the procurement time, there is a simulated time delay between the tender request by a customer and the manufacturer sending the tender to a special component supplier.

Agents. The procurement is initiated in the ETO order.

Input and output information. The input information for the procurement is the delay for triggering the tender for special components. The output is the trigger for the tendering of special components.

Interaction. The event trigger is the responsible for the interactions among agents.

Technical, conceptual and detailed design

Why? The product development is a fundamental part of the MTO/ETO value chain. Particularly for ETO products, the proper management of the iterative product development process is key for success. The product development is treated as a project, and multiple projects can compete for resources in the same manufacturing environment.

What? It is very difficult to map the product development process, particularly because multiple components have to be designed, whose specifications can vary significantly. The level of available information is highly scarce and uncertain. The design is an integral part of the order agent. In broad terms, we can state that the behaviour of the ETO order is determined by the product development. For MTO orders, a customization task corresponds to the design stage.

How? The technical, conceptual and detailed design (product development/order specification detail) have been simulated from an aggregate perspective, using a continuous SD approach, and the model developed by Rodrigues et al. (2006). A formal discussion about the selection of SD as a simulation method for the product development stage can be found in Paper C. These activities make use of the expertise of project developers, modelled as agents (human or composed artefact in the system decomposition). The level of experience of the developers involved in the project affects the productivity in the design development. The absence of these human resources is reflected in the design execution and completion.

Agents. The product development gives the dynamic behaviour to the ETO order. In the MTO orders, a simple stock and flow diagram represents the component customization.

Input and output information. The input information for the SD model in the ETO agent corresponds to the information that exists in the order as a result of the tendering request (initial order assessment). The input information includes the number of components to be designed – initial workload (Paper C), workload conceptual design (Paper E) -, the product development rate – workflow normal (Paper C), normal workflow (Paper E) -, the rejection rate – rejection normal (Papers C and E), the design obsolescence, and the inclusion of the new components to be designed – change in scope (Paper C), change rate (Paper E).

The output information corresponds to the trigger for the start of manufacturing, when the stock of the finished components equals the number of components that must be designed for a specific order.

Interaction. The finished components stock sets when the product development has finished. An event that is internal to the order (ETO and MTO) monitors the levels of the stock and flow diagram to signal when the product development has finished. After the quotation has been accepted by the customer, when it requests new components to be designed, or components to be changed upon revising the product design, the stock of work to be done is increased and the event that monitors the levels of the work finished is restarted. When components have been designed, these are prepared to start manufacturing. As new components can be required by the customer, the signal for the start of manufacturing can occur more than once. It occurs when the customer accepts the quotation – the accepted components proceed for manufacturing, according to scheduled – and when the added and/or altered components have been accepted by the customer.

Contract/order management

Why? The order management is a critical activity for the management of all activities that relate to the orders of products and to assess the status of an order inside the value chain nodes.

What? At the supplier level the contract/order management allows understanding the delivery status of the components ordered from the manufacturer. At the manufacturer agent, it allows assessing the stage of development of the MTO and ETO orders, the assessment of inventory levels, and confirming the purchase of quoted components at the suppliers. It also allows signalling when a customer withdraws an order.

How? The contract/order management function is modelled using an event that triggers the request for the status of an order. Another event signals when an order has been delivered or when a customer withdraws an order, to remove the customer from the orders waiting list.

Agents. Contract/order management exists inside the manufacturer and the supplier agents. Inside the customer agent there is a message sent when the customer receives the order or when it decides to withdraw the order.

Input and output information. At the manufacturer level, the input information required is the execution of an event, soliciting the status of an order or its withdrawal. At the supplier level corresponds to confirming the purchase of components. The output information consists of information about the status of an order. At the customer level, the order management can signal the withdrawal of an order when the manufacturer cannot comply with the required delivery dates or when it takes a long time to reply to an order tender request.

Interaction. The event trigger is the responsible for the interactions among agents.

Purchasing

Why? Purchasing corresponds to buying all the goods that the company needs to manufacture the products.

What? The purchasing function allocates the cost of the purchased components and the raw materials used for the manufacture of the products to a certain order.

How? The purchasing order consists of a function that is executed when the manufacturer receives the supplies.

Agents. It exists in the manufacturer agent and in the order agent. In the manufacturer agent it consists in allocating the cost of the generally used raw materials. Inside the order, it allocates the cost of the special and standard components ordered.

Input and output information. It requires the cost information for the raw materials and other components. As an output, it adds the cost of the purchased raw materials and components to the cost control function.

Interaction. An event upon the receipt of the raw materials and special and standard components triggers the execution of the purchasing function.

Manufacturing and assembly

Why? These are critical activities for obtaining the final product. Without these activities and the resources they use, it is impossible to fulfil the customers' requests.

What? Detailed or high-level mapping of the manufacturing and assembly activities permit their modelling. The start of the manufacturing at the manufacturer may depend on the completion (or partial completion) of the design activities. At the supplier level, the manufacturing and assembly of components start as soon as the manufacturer confirms an order.

How? Manufacturing and assembly activities have predominantly been modelled and simulated using a DES approach, given the strength of this modelling and simulation method in process modelling and tracking the status of entities and resources in the shop floor (Venkateswaran and Son, 2005). For MTO orders, processing times on different machines are known. For ETO orders, and to consider the variability that can be verified, routing and processing times of the components internally produced are randomly selected from combinations available. A high variability in the processing time in the ETO case is considered.

Similarly, the assembly time is known for MTO products. In ETO products, the assembly time is a function of the complexity level of the orders, information that exists in the order as a result of the tendering request (initial order assessment). In ETO products, during the assembly operations, errors in the integration of the components can be detected. These errors require the re-design of some components. The redesigned components must be re-manufactured and finally integrated in the assembly.

If it is available, all this detailed information can be well captured by a DES approach. However, successful modelling and simulation of inventory and production related activities using an SD approach has been reported by Sterman (2000). This is a good alternative when a detailed mapping of the shop floor processes is not possible, and a system wide perspective, and a global understanding of the production system are desirable (Kibira et al., 2009).

Considering this, at the manufacturing and assembly level, we argue that SD and DES can be successfully used, depending on the desired level of detail for the shop floor process mapping, and levels of aggregation of the input data available for the model.

Agents. Manufacturing and assembly activities exist at the manufacturer and supplier agents. At the suppliers, a high-level simulation has been considered, as it was impossible gathering detailed information about the suppliers (lower visibility than from the manufacturer).

Input and output information. Depending on the selected modelling and simulation approach the required input information varies. For a DES modelling approach, detailed information about the routing of components, required materials, the processing and assembly times is required. If an SD approach is deemed appropriate, general processing rates and material use per product are the required input information. The output information from the manufacturing and assembly operations consists in the information that these activities are finished, and the products are ready for testing or delivery. Additionally, signalling that errors have occurred during manufacturing is also possible, depending on the selected modelling and simulation approach.

Interaction. An event triggers the beginning, and another detects the end of the manufacturing and assembly activities.

Testing, delivery, and installation/commissioning

Why? These activities are very important for the MTO/ETO sector as these ensure the proper functioning of the products, their delivery to the customers and their installation at the customer's site, if applicable.

What? The testing activities are given by a delay that simulates the testing process. The transport activities reflect the transport of orders between the supplier and the manufacturer and between the manufacturer and the customer. The transport can use transport agents (human or composed artefact in the system decomposition level), which are the different transport means. The installation/commissioning is also given by a delay.

How? DES has been the method selected for modelling these functions, given its strengths in modelling logistics activities.

Agents. Inside the manufacturer agent and the supplier agent (transport).

Input and output information. Distance to the customer or manufacturer or location of the customer or manufacturer, time for the testing and installation/commissioning, and resources needed are the input information. Output information consists in signalling the delivery of the order, so it can be removed from the orders waiting list.

Interaction. Event triggered. When the customer receives the order, it sends information to the manufacturer that can close the order and remove it from the orders waiting list. Information about the accomplishment of the order and its timely delivery is kept.

Project management

Project management is a broad activity that has been divided into five groups of activities by the Project Management Institute, in the PMBOK® Guide: initiating, planning, executing, monitoring and controlling, and closing (PMI, 1996). For this, the project management is not addressed through a single function, but by all the functions that have been referred and the planning and cost control functions that will be described afterwards. According to the PMBOK® Guide, the initiating processes encompass recognizing that a project or phase should begin and committing to do so. For this, the events that control the start of design activities are initiating processes. Initiating processes are predominant at the beginning of the project. The planning processes are those that envision keeping workable conditions to accomplish the project execution. Though these processes are also predominant at the beginning of the project, they extend to the whole project, until the start of the project closing processes.

The executing processes are the longest in time and encompass the coordination of the resources to achieve the plan. These processes are addressed by the execution of functions for the allocation of resources to the projects, particularly the allocation of project developers to the design activities. The workforce allocation functions are executed when a new project starts and the details of the implementation of these functions can be found in papers C, D, and E. Ordering of materials and components are also functions that are included in the executing processes. The controlling processes encompass ensuring that the project objectives are met and taking corrective measures when required. This is addressed through the re-execution of the workforce allocation functions. Finally, the closing processes formalize the acceptance of the projects, to bring those to an end. For this, the acceptance of the orders by the customers, after the installation/commissioning activities, corresponds to the closing of the process.

Planning

Why? As previously mentioned, planning is one among the project management processes. It is a key activity that extends throughout the whole project.

What? The planning activities start as soon as an order enters the manufacturer system. First, to accomplish the initial product design in ETO products or for the customization activities, the planning activities calculate the number of project developers needed to accomplish the timeline defined by the customer. Additionally, the planning activities are responsible for calculating the amount of raw materials and components needed for manufacturing and assembly; and for assessing the available capacity on the shop floor to accommodate the manufacturing and assembly activities. A backward planning approach is considered in the scope of this work. When the limiting capacity factor at the shop floor are the available shop floor employee hours, the planning function considers the temporary hiring of workers.

How? These activities are executed through multiple functions. First, there is the allocation of project developers to the design/customization activities. A re-assessment of the allocation function can be performed when a project developer becomes absent or when the design due date is approaching. Then, another function assesses the amount of required raw materials and components for the manufacturing. Though these functions are executed immediately after the design activities, the order (executing process) is placed with the suppliers only upon confirmation from the customer. The production planning is executed after the design activities, to assess if the due date required by the customer is achievable, and if not, when is the best possible delivery date, and to assess when should production start, considering the availability of materials and components. Planning activities consider the dates promised by the suppliers.

Agents. Inside the manufacturer agent.

Input and output information. For the allocation of the project developers, the required information is the number of available project developers and their internal state. Calculating the needed raw materials and components requires as input the bill of materials of the product, and the inventory levels at the manufacturer. For the shop floor planning, information about the hours available in each workstation are required.

Interaction. Event triggered.

Cost control

Why? Cost control functions are relevant to maintain track of the costs allocated to the orders and to estimate the cost to be charged to the customer upon the order delivery.

What? Cost control is partially addressed in the developed models. This is because there is no feedback mechanism implemented that allows initiating an action when the cost deviates from the expected. Hence, only the overall cost calculation is made for the orders, considering the order handling costs, components and raw materials used, the number of project developers allocated to the order and the number of hours these have to work in a specific order, machine running costs, shop floor employees allocated to the manufacturing and assembly, transport costs, tools cost used in commissioning, cost of staff in the commissioning and cost of temporarily hired employees. The cost calculation structure may include components as the initial investment in machines, and the costs associated with the replacement of tools.

How? A function is used to calculate the estimated order costs and the real order costs during the project progression.

Agents. Inside the manufacturer agent.

Input and output information. The cost calculation function requires information regarding all the above listed costs.

Interaction. An event upon the entry of the tender request triggers the execution of the order cost estimate. During the progression of a project (order), multiple updates to a total real cost variable are done through the execution of events.

A summary of the use of the different simulation methods across the primary and support activities in the MTO/ETO value chain is presented in Figure 3.4.

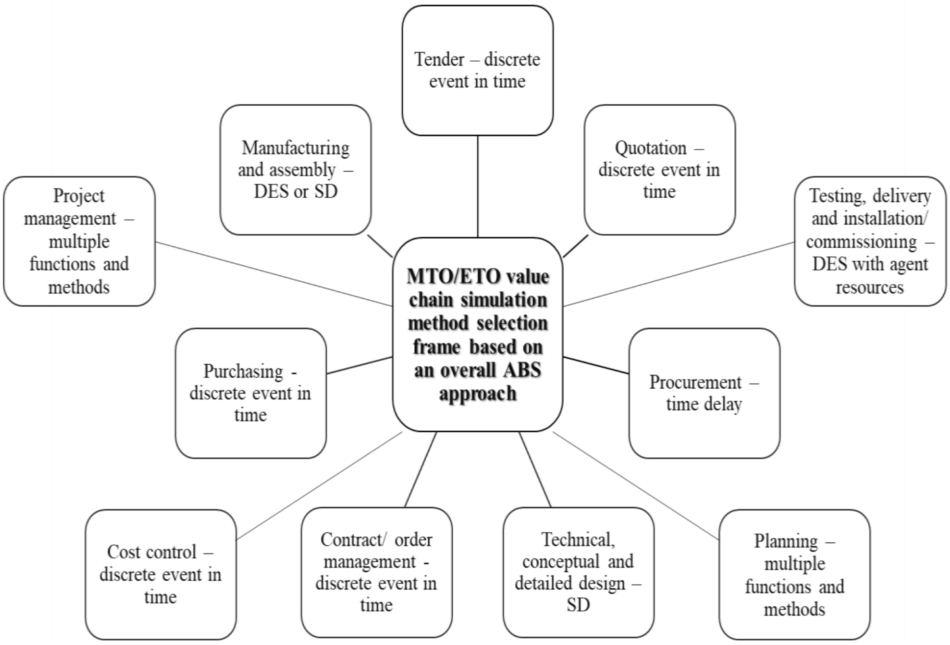


Figure 3. 4. MTO/ETO value chain simulation method selection frame, considering the primary and support activities.

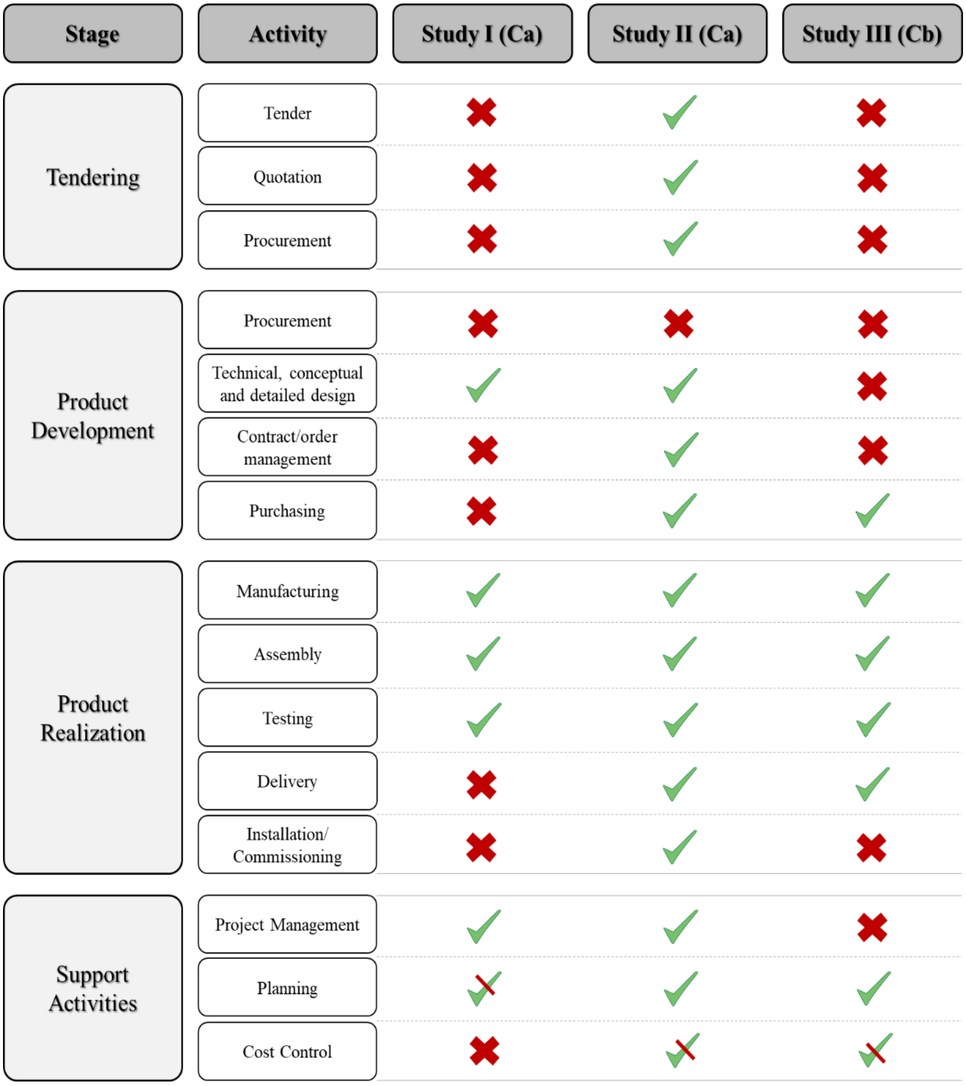
The discussion which has been presented so far arguments about the selection of appropriate simulation methods to represent the varied primary and support activities which have been identified for the MTO/ETO value chains. This discussion is critical in the context of this thesis, as a proper justification for the choice of the simulation methods is required to enhance the need for a hybrid simulation approach. From the above discussion, some key conclusions can be retrieved:

- A discussion which is substantiated on answering the key questions Why? What? and How?, and on expressing in which supply chain nodes the activities are included, the input/output information for the activities, and how interactions are established with other activities or agents, is able to justify the simulation methods that have been used;
- An enterprise wide solution, and a supply chain perspective can be obtained when using a hybrid simulation approach, as there is the possibility to represent functions/activities which are very different, without falling in an unnatural use of the simulation methods – it is possible to extract the best features of the simulation methods, while avoiding their downfalls;
- The discussion is based on the adequacy of the simulation methods in fitting the simulated activities, as reported in the existing literature.

A sequence diagram for the interactions established among the activities in the context of the hybrid MTO/ETO simulation model has been published in Paper E. A simplified version of the model can be considered if only the MTO value chain, through the MTO part of the sequence diagram, is contemplated.

3.2. Research design

For the purpose of testing and validating the models developed in the context of this thesis, three studies (Study I, Study II and Study III) were undertaken and data was retrieved from two different organizations (Company A – Ca, and Company B – Cb). The analysis focused on the different stages and the activities of the internal and external MTO and ETO supply chains, as Figure 3.5 shows. Studies I and II were conducted at Ca. These focused on the combined MTO/ETO supply chain. While Study I considered the internal supply chain of the focal company, Study II had a more extended view, by including the external supply chain, and considering the actions of customers and suppliers. Study III was conducted at Cb and focused on the MTO supply chain, therefore excluding from the analysis all product development and tendering activities.



Stage	Activity	Study I (Ca)	Study II (Ca)	Study III (Cb)
Tendering	Tender	✖	✓	✖
	Quotation	✖	✓	✖
	Procurement	✖	✓	✖
Product Development	Procurement	✖	✖	✖
	Technical, conceptual and detailed design	✓	✓	✖
	Contract/order management	✖	✓	✖
	Purchasing	✖	✓	✓
Product Realization	Manufacturing	✓	✓	✓
	Assembly	✓	✓	✓
	Testing	✓	✓	✓
	Delivery	✖	✓	✓
	Installation/ Commissioning	✖	✓	✖
Support Activities	Project Management	✓	✓	✖
	Planning	✓✗	✓	✓
	Cost Control	✖	✓✗	✓✗

Figure 3. 5. Focus of the studies developed in this thesis, considering the stages and activities of the MTO and ETO supply chains.

The selection of the case studies is critical to understand and maximize the knowledge about the phenomena being studied. This requires a set of criteria that case study candidates should comply with in order to be qualified to serve as the basis for the study (Gosling et al., 2014). In this thesis, the MTO/ETO supply chain is the unit of analysis, which means that case study candidates must operate under one of these (or both) strategies. The selection of the two case studies was, for this, based on the goodness of fit of the features of the candidate cases in the literature collected features for the MTO and ETO manufacturers. After identifying the case studies, their supply pipelines and customers' features were studied to determine the requirements for the modelling exercise.

Despite focusing on the core stages and the activities of the MTO and ETO supply chains, the intent of the three studies was different. In the following sub-sub-sections, the intent of the three studies is addressed, alongside the detailed description of the case study companies, Ca and Cb.

3.2.1. Study I

Study I was conducted at the company Ca, whose representation is in Figure 3.6. Ca is an advanced manufacturer of intralogistics solutions, including customized high-technological conveyors, packaging and robotized palletizers solutions for the food and chemical industries, and operates on a combined MTO and ETO basis. It operates in a Business-to-Business (B2B) value chain, as its customers are other business units that integrate the intralogistics solutions provided by Ca in their own production processes. For this, complying with the agreed delivery dates is critical for Ca's success. The solutions required by the customers can be selected from existing portfolio products or can alternatively be fully customized to comply with a specific situation. This promotes a low volume manufacturing of the products, but with a high mix. It is not uncommon that some solutions are only manufactured once. Furthermore, it operates with long flow times that can vary from a couple of weeks to months, under a highly variable demand pattern, often with uncertain product features, lead times and processes duration. Production starts when a new order is placed by a customer. Only small scale and general-purpose components are available in inventory. Other components are manufactured to order or ordered to the suppliers upon order receipt. The delivery of the products to the customers is made by a specialized commissioning team that installs and tests the equipment at the customers' facilities. The commissioning stage is managed by the focal case study company.

The focal company operates in a single facility, in a process layout, job shop, and uses general purpose equipment for product manufacturing. In the shop floor, the machines are grouped according to the function they perform, in a total of six Work-Centres (WCs), including the assembly, which is mostly manual. There is a different number of machines/working stations in each WC - two in WC1, four in WC2, one in WC3, one in WC4, three in WC5 and two in WC6. The standard portfolio products, that can undergo a small customization process have different routes and processing times in the shop floor. For the purpose of this study, seven standard product families have been considered, each with a different number of components, routes, and processing times. Quality inspection was considered to occur after each operation was performed. The facility working hours were considered to be from Monday to Friday, from 7 am–12 pm to 1 pm–7 pm.

In an ETO basis, the special projects are the unique products that undergo a product development process, including the product specification, design, and selection of materials. Multiple interactions with the customers exist and the product requirements can often be changed. The products are developed and customized to the customers' requirements by a specialized team. Special projects and standard products compete for resources in the manufacturing and development/customization levels. Alternative machine resources may need to be used in the special projects. When labour shortages are expected, the focal manufacturer subcontracts specialized workforce, with an implied extra cost for the temporarily hired employees.

On the supply side, the focal company interacts with three types of suppliers: raw materials, standard components and special components. The raw materials suppliers are responsible for supplying the raw materials that will be processed to obtain the components needed for the assembly of the final product. In the models developed it was considered that one unit of raw material was required to manufacture one component. The standard component suppliers are those suppliers that are specified for components that exist in the standard products, but that are not kept in inventory. For the components in the standard products, the component cost and lead time are known. The third type of suppliers is the special component suppliers. These are responsible for producing components that are outsourced in the special projects. The cost and lead time for the component suppliers is unknown upfront. For this, a tender request occurs initially to a supplier, followed by receiving the quotation when the supplier sets a cost and estimated lead time for the component.

In Study I, the purpose was to explore the MTO/ETO internal value chain of the focal company. For this, the interactions with customers and suppliers were neglected. An infinite supply of materials was considered and alterations to the special orders were made at specified points in time, during the project development.

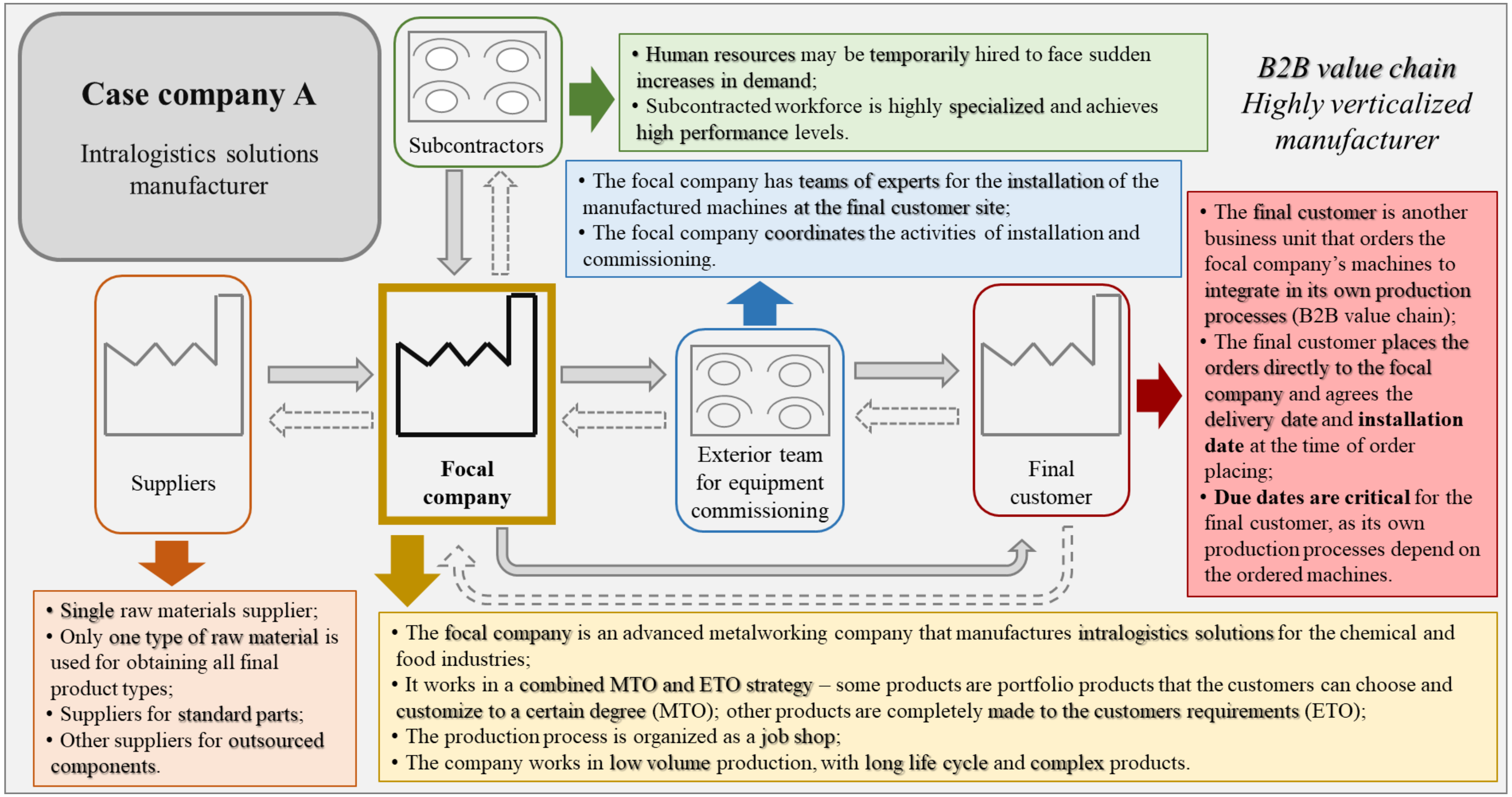
Study I also neglected the backward flow of materials and information from the manufacturing stage to the product design. For this, errors discovered during manufacturing that required the redesign of the components were not considered. A key operational concern in the MTO/ETO environments was explored, through the consideration of the product design stage: the sequencing of jobs on the shop floor. In this study different scenarios and sequencing rules were considered, and the performance of the focal company was measured for three key performance indicators: tardiness, resource utilization, and WIP levels. The planning support function was partially addressed in Study I. This is because the model considered the allocation of the resources to projects but did not consider their scheduling. As soon as an order entered the system, it immediately started customization and project development. When these stages were finished, their manufacturing started immediately, regardless the state of the shop floor. To assess the significant differences among the sequencing rules, a one-way ANOVA followed by a Tukey-Kramer’s test were performed. To assess the relevant system parameters related to human resources and project development with impact in the obtained performance measures, a Design of Experiments (DOE) analysis was used.

The data used for the case study was obtained from a data repository from the company that has been collected in the context of other projects. The data has been assessed and deemed appropriate in the context of this work. When data was not available, it has been considered to follow certain probability distributions that are standard for the simulated processes and considering parameters for those distributions that were in line with the available data. Information about some processes was obtained through direct observation of the operations, and informal meetings with the company administrator and the operations manager.

3.2.2. Study II

Study II was also conducted with Ca. This study encompassed the use of a model that was an extended version of the model developed for Study I. This model allowed including the actions of suppliers and customers, which increased the similarity between the model and the real case being studied. The model considered different supply chain actors, according to the mapping of the MTO/ETO supply chain that was derived from the literature review. Customers placed orders and changed their requirements as needed. This had an impact on the product development process. Internally, errors discovered during the assembly process could have an impact in the product development, with alterations to the design of some components being required. From the suppliers’ side, the interactions depended on the type of supplier. Interactions with raw materials and standard component suppliers were very predictable, though some variability has been considered. For the special components supplier, there was the request for a tender, followed by the reception of a quotation with the cost and an acquisition time terms. The procurement of supplied components was considered during the tendering stage of the value chain. During the product development, specifically upon alterations to the design, no procurement has been considered.

The intent of study II was investigating the impact that projects with different determinants levels had in the performance of the company. In the proposed approach, the supply chain actors were agents, whose internal structures included different decision and transformation processes. The structure of the model from Study I was used to simulate the internal focal manufacturing environment, yet alterations were made to include the interactions with customers and suppliers. Besides Study II including the interactions with customers and supplier, the other differences between the model in Study I and the internal model of the focal manufacturer in Study II are as follows:



- **Human resources** may be **temporarily** hired to face sudden **increases in demand**;
- Subcontracted workforce is highly **specialized** and achieves **high performance** levels.

- The focal company has **teams of experts** for the **installation** of the manufactured machines **at the final customer site**;
- The focal company **coordinates** the activities of installation and commissioning.

- The **final customer** is another business unit that orders the focal company's machines to **integrate in its own production processes** (B2B value chain);
- The final customer **places the orders directly to the focal company** and agrees the **delivery date** and **installation date** at the time of order placing;
- **Due dates are critical** for the final customer, as its own production processes depend on the ordered machines.

- **Single** raw materials supplier;
- Only **one type of raw material** is used for obtaining all final product types;
- Suppliers for **standard parts**;
- Other suppliers for **outsourced components**.

- The **focal company** is an advanced metalworking company that manufactures **intralogistics solutions** for the chemical and food industries;
- It works in a **combined MTO and ETO strategy** – some products are portfolio products that the customers can choose and **customize to a certain degree** (MTO); other products are completely **made to the customers requirements** (ETO);
- The production process is organized as a **job shop**;
- The company works in **low volume** production, with **long life cycle** and **complex** products.

Figure 3. 6. The case company A and its position in the supply chain.

- The workforce management model was simulated in SD in Study I, and in Study II a set of business rules was considered. This is because the focal company subcontracts workforce in discrete points in time, according to the demand needs. For this, a function allowing the temporary hiring of shop floor employees was deemed more adequate;
- In Study II, the orders included information about the project determinants;
- The planning function in Study II considered the shop floor capacity available for the manufacturing stage and the due date of the orders for the scheduling of the operations. For this, in Study II there was a list of orders waiting to start manufacturing, that was inexistent in Study I;
- Cost control was partially addressed in Study II, through the implementation of a function that allowed calculating the total costs of the orders.
- The stock and flow diagram simulating the product design activities has been refined in Study II.

In the model used in Study II, the planning and coordination activities were implemented through business rules (heuristics). A Monte Carlo sampling method was used to assess the impact of different model input parameters, the project determinants, in the model performance measures. The data collection methods were similar to Study I. Despite this, the dataset used in Study II was more extensive, as it included general information about suppliers and customers' features, and the project performance determinants.

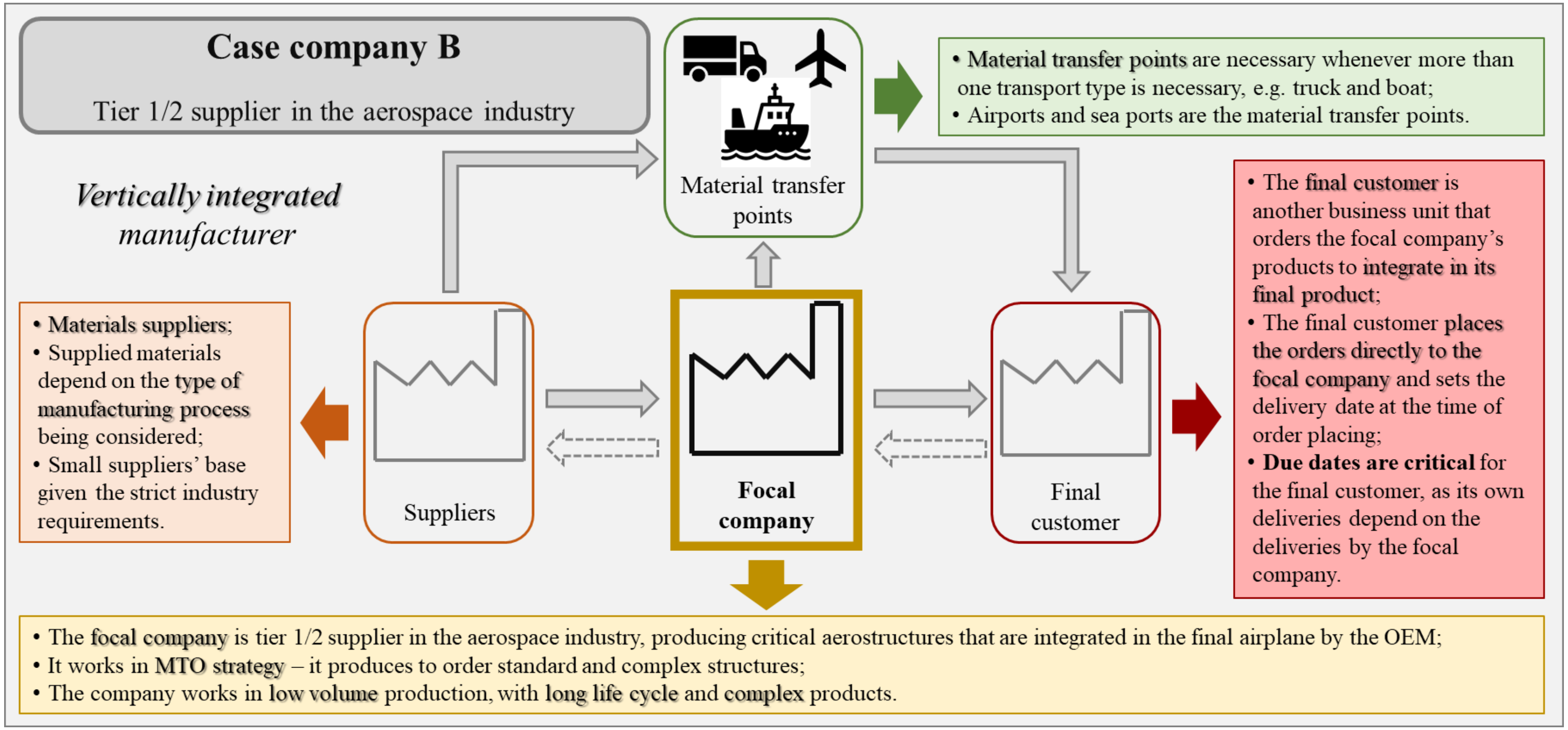
3.2.3. Study III

Study III was conducted at Cb. Cb is a tier 1/tier 2 supplier in the aerospace industry for commercial aircrafts, and its supply chain is represented in Figure 3.7. It is responsible for supplying highly complex and high sized aerostructures, fabricated using carbon-fibre composites, to an airframe Original Equipment Manufacturer (OEM) that assembles the final aircraft. The classification of the Cb as tier 1 or tier 2 supplier depends on the type of products being supplied. Though producing standard products, given the size and value of the final product and the erratic and low demand volume, Cb produces to order. For this it works with low volume and low mix production. The focus of the analysis is at the supply chain level, meaning that all details possible about transport activities, material and information transfer have been considered.

Cb's supply chain is global. It has suppliers worldwide and exports 100% of its production to a single customer, the OEM. It operates in two plants, located in the same city. One of the units is dedicated to the manufacture of machined metal structures, while the other is dedicated to composite material assemblies. The composites plant is the focus of the Study III. Only one product type is considered in the context of the case study, with a long manufacturing time. The plant operates continuously, seven days a week, and 24 hours a day. There are three shifts to ensure production at all times. Quality is key for the aerospace industry. For this, the focal manufacturer must work with zero defects.

Due to the relevance of composite materials to the future of the aerospace industry, the focal manufacturer became interested in updating its composites manufacturing process. The focus is to use more sustainable manufacturing processes, associated to a more sustainable supply chain. Currently, the focal manufacturer is using a composite manufacturing process based on an autoclave curing technology that, despite providing high quality components, entails high manufacturing costs and consumes many resources. To implement a more sustainable supply chain, Cb intends to assess the impact that different composites manufacturing processes, associated with the supply of different materials, can have on the supply chain sustainability.

On the supply side, Cb interacts with material suppliers. For the purpose of the study, different manufacturing processes are associated with varied material suppliers. This implies that each manufacturing process will encompass a different supply chain structure, with diverse supply times, and material requirements per unit of final product. This has implications in the supply chain costs, materials and component flow times, environmental, and social costs.



- Material transfer points are necessary whenever more than one transport type is necessary, e.g. truck and boat;
- Airports and sea ports are the material transfer points.

- Materials suppliers;
- Supplied materials depend on the type of manufacturing process being considered;
- Small suppliers' base given the strict industry requirements.

- The final customer is another business unit that orders the focal company's products to integrate in its final product;
- The final customer places the orders directly to the focal company and sets the delivery date at the time of order placing;
- **Due dates are critical** for the final customer, as its own deliveries depend on the deliveries by the focal company.

- The focal company is tier 1/2 supplier in the aerospace industry, producing critical aerostructures that are integrated in the final airplane by the OEM;
- It works in MTO strategy – it produces to order standard and complex structures;
- The company works in low volume production, with long life cycle and complex products.

Figure 3. 7. The case company B and its position in the supply chain.

As the purpose of the study is assessing the impact in the supply chain sustainability of adopting different composites manufacturing processes, all actors in the supply chain are considered, and a high-level modelling approach has been adopted. The customer and the focal manufacturer are fixed; however, the suppliers and the material transfer points depend on the material being supplied, associated with the manufacturing processes being studied. At the focal manufacturer, the resources used for the manufacturing functions vary with the manufacturing process being considered.

Study III is a joint effort that was part of a major project, the IAMAT. Most of the data considered for this study has been provided by other partners in the project. Data collection methods for the case study included direct observation of the plant operations, observation of experimental processes at laboratories, informal meetings with project work package leaders, formal meetings with production planning engineers working at the manufacturing plant, and workshops. Complimentary information was collected from publicly available sources and documentation.

3.2.4. Context setting

Table 3.3 presents a summary of the contents of the thesis studies and development stages, as reported in sub- sections 3.1 and 3.2. The purpose of each study, the case company involved, the research questions addressed, and the paper's coverage of the topics is identified.

Table 3. 3. Overview of the thesis research stages and studies, purpose, case companies included, research questions addressed, and papers' coverage

Study/Stage	Purpose	Case company	Research Questions addressed	Papers
Literature review	Assessing the modelling requirements of the MTO/ETO supply chains and collecting information about the available modelling methods	N/A	1, 2	A, B
Study I	Modelling the internal manufacturing environment in the MTO/ETO strategies and assessing the impact of the different sequencing rules in key performance indicators	Ca	2	C
Study II	Extending the model from Study I to the external supply chain level and assessing the impact of performance determinants in the system performance	Ca	1, 2	D, E
Study III	Assessing the sustainability impact of different manufacturing processes in the MTO supply chain and aiding in the selection of the manufacturing process considering supply chain dynamic conditions	Cb	2	F, G

The literature review was the basis of the thesis and allowed establishing the requirements for the modelling exercise for MTO/ETO environments, alongside identifying the modelling methods, their capabilities and shortcomings. It was an exercise independent from the case study companies and addressed both research questions that guide this thesis. Papers A and B focused on the topics covered by the literature review. Paper A provided an overview of the tools for performance assessment in complex manufacturing environments, while paper B was a structured review of the designs for hybrid simulation models, the strengths of hybrid simulation and the main challenges that exist.

Study I was addressed in paper C, which focused on the detailed explanation of the model for the internal supply chain of the focal manufacturer. It addressed research question 2. It focused not only in identifying the key functions to be modelled in the MTO/ ETO internal supply chain, but also in assessing the adequacy of using a hybrid simulation approach for modelling these manufacturing environments.

Papers D and E focused on Study II, with paper E being an extension of paper D. This Study extended the work from Study I to the external MTO/ETO supply chain. The focus of this study was on both research questions. On one hand, was important to derive a set of key performance determinants to be modelled (addressing research question 1); on the other hand, there was the need to understand which key processes had to be included in the model from Study I, to extend it to the external MTO/ETO supply chain.

Finally, papers F and G were the result from Study III, and paper G is an extension of paper F. Study III focused on the MTO supply chain. Its purpose was different from the previous studies. It focused on a more strategic view of the supply chain, without considering in detail the transformation processes in the focal manufacturing company. This study addressed a different type of MTO companies. While in the studies I and II, the MTO part of production was associated with low volume and high mix manufacturing, Study III focused on low volume and low mix manufacturing. Study III represents those MTO manufacturers that wait for an order to arrive to start production, but not due to the high mix of products; it is due to the large size and the high value of the products manufactured, that cannot be kept in stock.

3.3. Summary Hierarchical and Hybrid Performance Assessment Model (H2PAM)

The H2PAM, summarized in Figure 3.8, is a novel framework for the assessment of different performance dimensions in complex manufacturing environments. It is oriented for the MTO/ETO value chains. The term hierarchical has been selected since multiple levels of analysis with varied details are modelled; hybrid is because a hybrid simulation approach has been selected as a research method, for targeting the different processes in the MTO/ETO value chain. Multiple dimensions are considered in the model, including space, time, and measure. Space corresponds to the geographic spread of the value chain

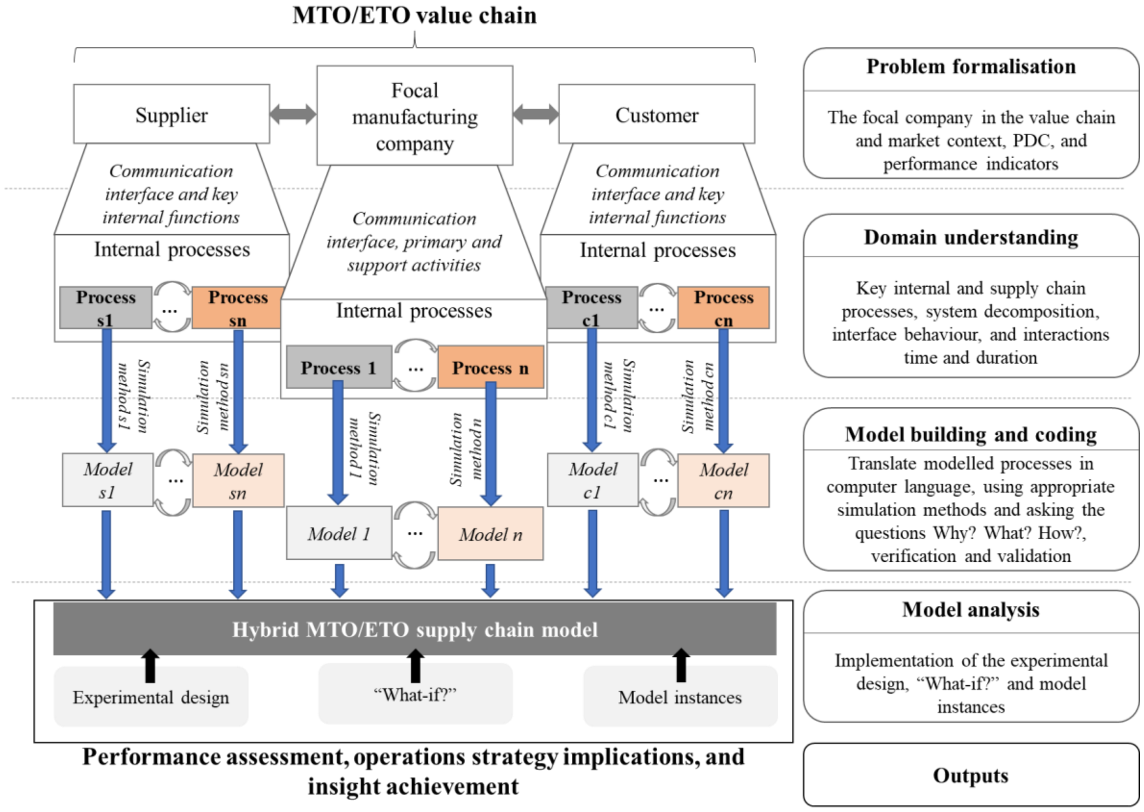


Figure 3. 8. Summary H2PAM.

nodes and the physical interactions among them. Time corresponds to the time variation of the behaviour of the model; and measure corresponds to the performance indicators that are assessed and with what level of detail. The H2PAM considers the stages presented in the framework from Figure 2.5, and the system decomposition approach in Figure 3.3, though only the top-level hierarchy is represented, for the figure simplification purposes.

During the problem formalisation stage, the focal company is identified, alongside the context in which it operates and the remaining key supply chain nodes. Given the context of operations of the company, the PDC are identified and the key indicators to be evaluated. This stage basically sets the objective of the model. In the domain understanding stage, the system is decomposed according to the decomposition system in Figure 3.3, proposed in this work. This is key to establish the boundaries of analysis, the key processes to be represented, the model assumptions, and the time horizon and duration of the interactions among the supply chain nodes. The important interface functions that insure the information and material transfer among the supply chain nodes are identified. During this stage, the modeller must check for conceptual inconsistencies in the model. The model building and coding follows, to which corresponds establishing the appropriate modelling and simulation methods that best represent the intended features for the modelled processes, functions, and activities. After the model is verified and validated, the model analysis uses the model instances collected during the inputs stage, the established experimental design and the questions to be asked to the model. The output of the H2PAM consists in the performance assessment, evaluation of the implications of a given manufacturing strategy, and the system insight achievement.

Following Bertrand and Fransoo (2002), the scientific relevance of this work lies in the study of a process/problem that has been addressed before, but through a new solution approach, though using well established methods. The practical relevance of the proposed model lies in the reference to real-life situations to which the model is applicable. Also, the use of a hybrid simulation approach reduces the need to compromise on the level of abstraction of the models, which permits coming closer to addressing the complexities of the real-life operational processes. The relevance of the model can be recognized not only by the results is gives, that can be of key relevance for the decision-making process, but also by the insight into the processes that is achieved throughout the modelling exercise.

The proposed H2PAM has been applied to two case studies. Though data which is specific to the case studies has been used, for results generalizability purposes, whenever possible, an effort has been made to compare the results obtained with the existing literature, as will be presented in Chapter 4 – Summary of papers and relation to the thesis. Also, the models have not been developed in line with the companies' specific processes, but in line with the general features of the MTO/ETO environments, as collected from the literature. Additionally, appropriate statistical techniques have been used to assess the model outputs, alongside the discussion with the case study companies to evaluate the progress of the work.

Chapter 4 – Purpose and contribution of produced papers

This chapter provides a summary of the papers that resulted from the developed research and their relation and contributions to the thesis. Each paper is presented individually, through an extended abstract. The full paper is provided in the appendices of the thesis. In the extended summary, the topics purpose, design/methodology/approach, findings and contribution to the thesis, research limitations, practical implications, and originality/value are explored.

4.1. Paper A: Evaluation of improvement actions impact on manufacturing operational performance

Purpose. Modern manufacturing environments are very complex and face multiple challenges that result from constant market changes, technological moves, and the activities of competitors. Companies must compete with shorter product life cycles, which enhances the need to adapt and create effective and efficient plans for their assets and resources, so that these become valuable for a period that is higher than that of the life cycle of the products being produced. For this, the purpose of this work is twofold. First, it proposes to understand which key tools, practices, and strategies are being used by companies to improve their performance in this demanding context and remain competitive. Second, it intends to settle a set of useful tools that can be used to develop models capable of predicting the future manufacturing performance.

Design/Methodology/Approach. Multiple papers are analysed to understand the key practices that companies are employing to deal with the product life cycle reduction. Those tools are summarized. For this, the scientific approach used in this paper was the literature review.

Findings and contribution to the thesis. The literature refers to multiple strategies used to improve the manufacturing performance, including the alignment of the actions at the manufacturing plant with the competitive priorities, continuous improvement initiatives, environmental concerns, delayed product differentiation, lean manufacturing, and the implementation of the Plan-Do-Check-Act (PDCA) cycle. Additionally, it is referred that the modelling of the system dynamics is a good strategy for controlling the actions of manufacturing systems. Considering the results from the literature review, it is established that a set of quantitative and qualitative methods (though with a higher focus on the quantitative methods) should be used throughout the work developed in the context of the thesis. The methods include simulation methods and a case study-oriented approach.

Research limitations. The literature review was not structured and did not include as many papers as desired. For this, a better understanding of the tools used by companies in practice can be achieved by a more structured and extensive review. Also, despite being pointed a set of methods to guide the research work, there is not a discussion towards their best fitness for the problem being considered.

Practical implications. In practice, there is no best approach to manage the increasing complexity introduced by the reduced product life cycle, nor a thorough discussion about the implications that the frameworks proposed in the literature have in the manufacturing performance. Despite this, there is an agreement in the cited literature that manufacturing companies must invest in becoming highly flexible.

Originality/Value. A novel approach to assess and understand the performance of complex manufacturing environments is proposed. The proposed approach highlights the need to use hybrid research methods to make the problem complexity manageable.

4.2. Paper B: Hybrid Simulation for Complex Manufacturing Value-chain Environments

Purpose. The real-world context of advanced manufacturing systems, which are more and more complex, entail many elements of human decision making, and require a global business optimization, have been pushing researchers to find alternative approaches to study these systems. Hybrid simulation approaches are one of the alternatives pursued by researchers; even so, there are many challenges in the area that must be addressed. The aim of this study is twofold. First, understand how hybrid simulations are being applied in the context of the manufacturing business performance, through the exploration of different hybrid simulation designs. Second, evaluate the key challenges and aspects that must be considered upon developing hybrid simulation models.

Design/Methodology/Approach. Given the fact that there is not a unified use of terms and definitions for hybrid simulation in the literature, which introduces great ambiguity for researchers, the method selected for the research was the structured literature review. Through a selection of terms that have been used in the literature for hybrid simulation (eg. multi-method simulation, combined simulation), the literature review allows gathering more information about models that have been developed throughout time, and how these models have been developed.

Findings and contribution to the thesis. A taxonomy of classifications for the hybrid simulation designs has been found in the literature, which is applicable to all possible combinations of the three simulation methods – SD, DES, and ABS. Those designs are interfaced, sequential, enrichment, and integrated. For each design, the levels of aggregation/coupling of the models involved, the sequence of execution of the models, and the information exchange details are presented. Also, the main challenges and possibilities when using hybrid simulation approaches are highlighted. Among the challenges, the literature often cites the need to well justify the use of hybrid simulations, since the models involved must be of equal importance to the overall goal of the simulation; the effort involved in the development of hybrid models, precision upon establishing information sharing among the models, conversion of time units, and the required knowledge about the different simulation methods. Despite this, many advantages come from the use of hybrid simulation, including improved flexibility during the model development, possibility of simulating different levels of aggregation, easier analysis of the model results, and possibility of exploring multilateral problems.

As a contribution to the thesis, the review undertaken was helpful to achieve insights into the hybrid simulation model building process and the types of issues that should be carefully considered, to avoid modelling inconsistencies.

Research limitations. Despite being comprehensive, the literature review may have excluded some relevant works. The selection of the papers to be analysed excluded all the papers that were not in the realm of manufacturing and its business-related activities. For this reason, models developed in other areas, as the healthcare, have not been considered. Consequently, more designs could have been found, or better insight into the details of the proposed designs could have been achieved. Additionally, a more encompassing explanation of the inclusion criteria for the models in each type of design should be presented.

Practical implications. The paper gives a summary of the literature that is useful for researchers developing hybrid simulation models. It addressed commonly referred topics that need to be addressed in hybrid simulation, contributing to the unification of the terms in the literature. Additionally, the proposed designs, being applicable to all combinations of simulation methods, can be considered by the researchers for a good grounding during the model development process.

Originality/Value. The proposed taxonomy of designs is based on existing literature, especially on Swinerd and McNaught (2012), and Morgan et al. (2017). Despite this, the authors solely focused, respectively, on the combinations SD-ABS and SD-DES. However, a close analysis of these works shows that the proposed designs, though sometimes named differently, were very similar and obeyed to the same constraints. For this, the proposed classification of designs unifies both views and extends to the application to all possible combinations of simulation methods in hybrid models.

4.3. Paper C: Hybrid modelling of MTO/ETO manufacturing environments for performance assessment

Purpose. Though being among the most complex manufacturing environments, the MTO/ETO value chains have been seldom addressed in the literature. It has not been until recently that these manufacturing environments have become the focus of more studies, due to the demand for highly customized products. The key to the success of these manufacturing environments are the engineering and production activities. For this reason, an integrated modelling approach for performance analysis and manufacturing system insight achievement, which considers both activities, is required. It is the aim of this work developing an integrated model for the MTO/ETO internal value chain activities. The modelling exercise permits achieving insight into the most relevant activities for these value chains, while originating a powerful tool for the performance assessment of key indicators of the system operating under different policies and product demand patterns, and assessment of the impact of relevant system parameters in performance.

Design/Methodology/Approach. A three-stage problem analysis is considered in this work. First, a hybrid SD-DES-ABS modelling approach is used to address the needs of a complex system that must handle diverse types of orders, processes and workforce allocation requirements. The second and third stages encompass the utilization of appropriate statistical techniques that allow comparing different scenarios and search for a solution for the problem being analysed. In the second stage, the results of the model running under different demand scenarios and queuing policies are assessed using a one-way ANOVA analysis followed by a Tukey-Kramer's test with pairwise comparison. This allows understanding significant performance variations under the considered operating policies. Third, a full factorial DOE analysis is used to determine relevant process parameters that influence the system performance.

In the proposed hybrid model, there are six modules: order prioritization, order specification detail, production, workforce allocation, workforce management, and project developers. Each of the modules that exist in the model are aligned with some of the value chain stages and activities identified in Figure 2.2. Specifically, the tender activity is partially addressed in the order prioritization module, though in the model is considered that the order is fixed. The technical, conceptual and detailed design activities are addressed in the order specification detail and developers modules; the manufacturing and assembly are considered in the production module. The workforce allocation module is a component of the project management activity, while the workforce management is within the planning activities.

Findings and contribution to the thesis. The complexity of the combined MTO/ETO environments calls for the use of hybrid simulation approaches, so that the functions of very different nature that are key in these environments can be concurrently modelled and simulated. While the product development activities are better captured by an SD approach, the production activities are better captured by a DES model, and the project developers are better simulated as agents.

The results obtained from the model are varied. First, it is found that when only MTO orders are considered in the demand, the queuing policies obtain a performance level that is similar to that reported in the literature – the Earliest Due Date (EDF) policies outperform the others in terms of product tardiness, the Shortest Processing Time First (SPTF) rule achieves the lower WIP levels, and the utilization of the resources at the production level is independent of the queuing policy being considered. The First In First Out (FIFO) policy achieves the highest percentage of delayed orders, while the Priority Based -EDF (PB-EDF) rule achieves the lowest percentage of delayed orders. When ETO orders are considered, the assessment of the results becomes more difficult, as there is no single policy outperforming the remaining. One must point out that increasing the number of ETO orders leads the system to coming closer to the limit capacity.

The DOE assessment showed that the operational parameters at the shop floor level (e.g. number of shop floor employees) have a higher impact in the performance measures related to standard MTO products, while for the special projects, parameters related to the project development (e.g. percentage of the total available time allocated to the development) had higher relevance.

This work has a twofold contribution to the thesis. First, it represents the internal MTO/ETO value chain modelled through a hybrid simulation approach. Second, it achieves results that have practical implications for companies operating under this combined strategy.

Research limitations. The model has only been applied to one case study company, and the generalization of the use of the proposed framework is not possible. Additionally, the input data set used was specifically for the case study, which may result in different conclusions for other data sets. Despite these limitations the model has great room for improvement through enhanced functions and an extension to the external value chain level. Obviously, the adequacy of the simulation methods for the modelled functions can be discussed, and other alternatives may be more plausible in other contexts of data availability and desire to model different levels of detail.

Practical implications. From a practical point of view, the proposed conceptual framework can be used as a decision support tool, to aid managers working in the MTO/ETO environments anticipating the results of alterations in operational policies and procedures. Additionally, the modelling exercise is key to gain insight into the working principles of these environments.

Originality/Value. The proposed conceptual framework uses well proven methods to achieve an innovative solution to represent in the same model processes that are very different in nature. The product development process is rarely addressed concurrently with the production process, and it is found to be a major source of variability in combined MTO/ETO environments. This represents an enterprise-wide solution, even if restricted to the internal value chain.

4.4. Paper D: Towards a hybrid multi-dimensional simulation approach for performance assessment of MTO and ETO manufacturing environments

Purpose. Due to the growing relevance of customization as a source of competitive advantage, the MTO/ETO value chains have been receiving increasing attention. The simultaneous customer-oriented projects that compete for and share resources within the same manufacturing environment, make critical assessing the impact that different development projects and production related variables have on the manufacturing system performance. It is the purpose of this work extending the model proposed in Paper C to the supply chain level and propose a set of performance determinants that are key in MTO/ETO environments. Its purpose also lies in understanding the impact of different levels of those performance determinants in the extended hybrid model.

Design/Methodology/Approach. A hybrid simulation approach is used for the model development. The model builds on a general ABS approach, with the value chain actors being represented as agents. In line with the system decomposition in Figure 3.3, three major types of agents exist in the model: suppliers, manufacturers, and customers.

The behaviour of the supplier agent is determined by a set of business rules and a simplified DES model of production. The customer agent is the demand driver in the model. It is responsible for starting the tender request. The manufacturer agent is the most complex. It responds to the customer tender request through an order quotation and waits for the customer acceptance. It orders supplies of raw materials, standard components and special components suppliers. The other activities inside the manufacturer are aligned with those activities identified in Figure 2.2.

Findings and contribution to the thesis. In the paper, a set of six product design and development performance determinants are derived, including design/engineering workload, project type, design reuse, outsourcing, complexity, and experience/knowledge of technology. The results obtained from the model show that when ETO orders are considered, there is an increase in the utilization of resources – shop floor employees, machines and project developers. A higher increase is verified for the project developers, which when only MTO orders are present in the system, only dedicate to small customization activities. The time variation of the resources utilization is aligned with the presence of projects with different determinants in the system. Additionally, it is verified that the highest total cost of a project occurs for very high levels of workload and complexity, very low levels of design reuse, outsourcing and experience, and for the type of project integrating more types of product categories.

Research limitations. Some research limitations exist in this work. First, the model is applied to a single case company. Second, there is the need to increase the number of repetitions in the simulations to achieve more stable results. Finally, some of the product design and development determinants can make the definition of what a MTO order and what an ETO order are, ambiguous. As an example, if a very high design reuse is considered, does it make the order an MTO order, or an ETO order? Further details about the extent of the design reuse to be considered an ETO order should be determined.

Practical implications. For the practice, the model demonstrates that good performance predictions can be achieved by considering and classifying the projects to be developed. By assigning different levels to the design and development determinants, estimates about the system performance during the project execution and about the performance of the manufacturer towards its customers can be achieved. This can be particularly relevant for an MTO/ETO manufacturer, for predicting the manufacturing performance when considering accepting an order from a customer.

Originality/Value. The paper proposes a model that is an extension to the external value chain of the model proposed in Paper C. The model in Paper C is also refined in some functions and dimensions.

4.5. Paper E: Assessing the impact of performance determinants in complex MTO/ETO supply chains through an extended hybrid modelling approach

Purpose. Product design and production activities are highly intertwined in MTO/ETO environments. It is very difficult assessing the performance of these manufacturing environments without considering the effect of both types of activities. In line with Paper D, the purpose of this study is twofold. For this, it intends to assess the influence that the design/engineering activities have in the MTO/ETO supply chains; and to propose and assess the impact of a set of key performance determinants in these supply chains.

Design/Methodology/Approach. In this work is proposed a hybrid simulation approach that tackles the engineering and manufacturing/assembly activities in the MTO/ETO supply chain, and that integrates the three simulation methods: SD, DES, and ABS. The proposed model extends the model proposed in Paper C. In the developed approach, the supply chain actors are modelled as agents, whose internal structures include diverse decision and transformation processes. While the technical, conceptual and detailed design (product development) activities are simulated using SD, manufacturing, assembly, testing and commissioning are simulated using DES. Tendering, management, planning and coordination activities are implemented through business rules (heuristics). A Monte Carlo sampling method is applied to assess the impact of different model input parameters in the model performance measures. The data statistical assessment considered the use of histograms of the total project time, manufacturing and assembly time, and project costs. Central tendency measures characterizing the data have been retrieved and a parametric Spearman correlation was used to assess the statistical association between the random variables.

Findings and contribution to the thesis. This paper extends the Paper D, through a model improvement and thorough assessment of the results. When compared to Paper D, the performance determinants affect more model variables (e.g. in paper D, the experience/knowledge of technology determinant did not affect the deviation in the assembly time). It also extends the model proposed in Paper C to the supply chain level. By refining previous models and papers, this paper contributes to the overall goal set for the thesis of modelling and gaining insight into the behaviour of complex MTO/ETO environments. It also addresses with higher detail the communication mechanisms established between the models from different methods, through a sequence diagram.

As for the paper's findings, it has been found that the workload determinant had a big impact in the project time and total cost of MTO products and had no impact in the manufacturing and assembly time. This was a consequence of the fact that the manufacturing and assembly activities were only affected by the type of portfolio product being produced/assembled, and not by the number of design objects to be customized to the customer requirements. For ETO products, it was found that all determinants had an impact on the project time and total costs, while there was no evidence of association between the project type and design reuse determinants, and the manufacturing and assembly time.

Research limitations. Despite being valuable in the MTO/ETO supply chain performance assessment, the proposed model has only been applied to a case study company. For this, the generalization of results is not possible, as is common in simulation approaches. However, the results obtained are still pertinent because the case study company presents the main features of MTO and ETO companies referred in the literature. The model structure could be easily applied to other case companies. The levels considered for the performance determinants and the cost structure had an impact and biased the results, meaning that other input values for the levels could lead to different results.

Further improvements to this work should be well-thought-out. First, the model should be applied to other companies to promote results generalizability. Secondly, the results obtained in this work considered that any combination of determinants was possible, and that all determinants levels had equal probability of occurrence, which might not be applicable in real situations. Evaluating the model results considering constraints among the levels of the performance determinants would be a useful study. Complementary prediction tools, as machine learning algorithms, could heighten the results obtained. Furthermore, and as the model is very sensitive to the input data, a sensitivity analysis of the model to the input parameters would be valuable. An additional step to this work would be to find evidence of an association between the performance determinants and the model variables affected by those determinants. This could be achieved by enquiring the system experts about this issue.

Practical implications. The practical implications of this work are similar to those pointed in Paper D. The model shows that good performance predictions can be achieved by considering and classifying the projects to be developed and estimating performance measures associated with the different levels of the design and development determinants.

Originality/Value. Similar to Paper D.

4.6. Paper F: Towards a supply chain sustainability conceptual model for performance assessment: a case in the commercial aircraft industry

Purpose. Given the recent aerospace industry demands, commercial airplane manufacturers are now pushed to compete through more efficient supply chains to reduce emissions and airplane fuel costs. For this, it becomes critical investing in new product development initiatives that target these goals, including lighter and more efficient materials and manufacturing processes. Considering this context, it is the purpose of this work assessing the supply chain sustainability performance of a manufacturer in the aerospace industry, upon the introduction of new advanced composite materials and production processes.

Design/Methodology/Approach. A hybrid simulation approach is used to assess the supply chain performance for different scenarios, corresponding to different combinations of materials used in production and manufacturing processes. The supply chain actors are modelled as agents, whose location is real, and the transport resources are also modelled as agents, whose behaviour is defined by a state chart. DES is used for simulating the transport of materials between the supply chain actors and SD and business rules are used to represent inventory management and manufacturing functions.

Findings and contribution to the thesis. The work developed in this paper allowed achieving important insights about the sustainability performance of the different combinations of composite materials and manufacturing processes being considered in a case study. Relevant metrics as CO_2 emissions, energy consumption, global supply chain costs and workload have been evaluated, based on a Triple Bottom Line (TBL) approach.

This work represents the MTO supply chain of a major aerospace parts supplier. It consolidates the appropriateness of a hybrid simulation approach for representing processes that are very different in nature (e.g. transportation and manufacturing), through a simplified view. As the data available for the case study was reduced, it has been decided to maintain the representation of the production and assembly functions in an aggregate view, through an SD representation of the manufacturing and inventory management functions. This highlights the relevance in adapting the modelling exercise to the available information and data, as well the degree of detail required for the simulations. The modules from different methods included in the model were of equal relevance to the overall goal of the simulation and emphasize the need to address multiple issues when evaluating the performance of complex supply chains and gaining insight into their working principles.

Research limitations. Though addressing important sustainability metrics, it is important to extend the analysis to other performance metrics. Additionally, a conjoint assessment of sustainability-oriented metrics and business performance metrics (e.g. accomplishment of deliveries, delays in the deliveries) should be considered, as the survival of a business depends on multiple dimensions of performance. A purely sustainability-oriented assessment may hide some important performance drawbacks of a given combination of composite materials and manufacturing processes. Other scenarios of uncertainty still must be explored, as only steady-state conditions have been addressed.

Practical implications. The developed models have been applied to a real case study, which emphasizes their relevance as a decision-support tool. A sustainability assessment should be accompanied by a business performance-oriented analysis.

Originality/Value. The aerospace supply chains are seldom addressed in the literature, which creates a major research gap. For this, applying an innovative modelling and simulation approach in this context becomes extremely valuable. In line with the previous studies (I and II), the modelling exercise was key to achieve a better understanding of the MTO aerospace supply chain.

4.7. Paper G: Sustainability performance assessment in the commercial aircraft MTO supply chains: a hybrid simulation approach applied to the real case of an aerospace manufacturer

Purpose. While the MTO supply chains have been experiencing increased attention in the past few years, it is a fact that industries that commonly operate under this strategy, such as the aerospace, have been taking some steps towards improving their sustainability. As the increasing attention given to the MTO supply chains calls for the use of new dynamic methods to assess/predict their performance, adding to the performance assessment a sustainability-oriented perspective becomes relevant. Considering this, it is the purpose of this work developing a hybrid simulation model for the MTO supply chain performance assessment, considering the strengths and weaknesses of the different simulation methods. It is also the intent to apply the developed model to a real aerospace supply chain, make computational experiments using different scenarios to evaluate relevant performance indicators, and apply a Multi-Criteria Decision Analysis (MCDA) to predict the outcomes of the decision-making process, considering the quantitative indicators from the hybrid simulation model and different possible profiles of the decision-makers.

Design/Methodology/Approach. To tackle the requirements of supply chain functions which are very different in nature, a hybrid simulation approach has been deemed appropriate for the purposes of performance assessment. Given the real case study at hand, the impact of the use of different combinations of materials/manufacturing processes in the aerospace industry is assessed. While the overall structure of the model is built around an agent-based approach, the agents' internal behaviour is modelled using SD, DES, statecharts, and business rules. Different functions are considered inside each agent, including interface functions, planning/control functions, and production. While the interface functions ensure that proper communication and exchange of materials/products occurs between the supply chain agents, the planning/control functions that coordinate the internal agents' activities, are implemented using high-level business rules which are triggered by the execution of events. The transport of materials and products between the supply chain agents is modelled using DES. Production functions are implemented using SD, due to the high-level analysis requirements of the case study. The exchange of information between models from different methods is guaranteed by the execution of events and the shared variables.

While the hybrid simulation model allows estimating relevant performance indicators under different scenarios, it does not predict the outcomes of the decision-making process. For this, an MCDA technique, the AHP is used to assess the outcomes of the decision-making process, considering the values of the performance measures obtained through the hybrid simulation model, and the varied possible profiles of the decision-makers.

Findings and contribution to the thesis. Through this work, relevant insights about the MTO supply chains, especially the aerospace supply chain, are achieved. With a central focus on the sustainability of the manufacturing supply chains, this work gave important contributions for the dynamic supply chain performance assessment during the adoption of new materials and manufacturing processes. The manufacturing processes that have been considered in the case study were the autoclave (current technology in use at the case study company), the Vacuum Assisted Resin Injection (VARI), and the Vacuum Bag Only (VBO). Key performance indicators, associated with the three categories of sustainability -economic, environmental, and social - and other key indicators for MTO supply chains have been studied. Different scenarios considering the demand and supply uncertainty have been studied.

Being applied to a real case study, this work greatly contributes to the fulfilment of the objectives established for the thesis. It not only tackles the understanding of complex supply chains, but it also takes a step forward in defining an integrated tool for the manufacturing performance assessment. It does enhance the value and flexibility that a hybrid simulation approach gives upon analysing complex systems.

Additionally, it enhances the relevance of considering trade-offs among the complexity of the systems, the complexity of their representation, the availability of information about the systems being modelled, the required degree of detail for the models to serve a given a purpose, and the wideness of functions that the model intends to represent.

By combining the hybrid simulation models with an MCDA technique, the models show to be an important tool for the aiding in the decision-making process.

Research limitations. While this work addresses some of the issues and limitations of the work presented in Paper F, it does present some important limitations. First and foremost, the input data that has been used for the model experimentation was linearly scaled-up from the case study laboratory conditions. This immediately constrains the managerial implications that can be gained from the model results, and additional scale-up options should be explored. Furthermore, some improvements to the model should be considered, as the use of learning curves associated with the SD model, to consider the productivity of the workers as a key factor in determining the manufacturing systems' performance.

Practical implications. The developed models have been applied to a real case study, providing guidance towards the possible outcomes of the selection of the different manufacturing processes. Obviously, the managerial implications of this work are limited by the scale-up that has been applied to the model input data, but regardless of that, the decision-making process can have different outcomes, according to the profiles of the decision-makers. While the autoclave process demonstrates to be the most economically viable alternative, when it comes to the environmental and social categories, it is the VARI process that gives the most gains.

Originality/Value. This work is valuable in the sense that it considers unexplored topics, as the MTO supply chains and the aerospace industry. It additionally proposes an innovative hybrid model for performance assessment that uses well established simulation methods: SD, DES, and ABS. It represents an innovative approach not only by using a hybrid simulation, but also because it integrates the use of simulation and MCDA in a sequential way, to assess the possible outcomes of the decision-making process, during the selection of materials and manufacturing processes in a manufacturer operating in the aerospace industry.

Chapter 5 – Conclusions and future research directions

Throughout this concluding chapter, the main findings from the research studies and the implications of those findings for the MTO/ETO value chains are discussed. The main conclusions, research contributions, limitations and future research directions are presented.

5.1. Main conclusions

Nowadays, MTO/ETO manufacturing environments are constantly challenged by an increased business complexity. Assessing and predicting performance, while gaining insight into the manufacturing systems working principles become key goals for managers. Managers and decision-makers are, for this, in great need for tools that help them better understand the system's behaviour and evaluate the impact that changes in the manufacturing system have on multiple dimensions of performance.

In this work we have proposed the H2PAM as a performance assessment tool for complex MTO/ETO manufacturing environments. It is a framework that results from two main ideas/concepts: system decomposition and hybrid modelling and simulation. The system decomposition allows studying the complete system, yet by dividing the MTO/ETO complex manufacturing system into smaller units, with relevance, that make the problem manageable and improve the understanding of the system. This avoids leaving unstudied relevant parts of the manufacturing system. For the system decomposition is important to map the stages and activities of the value chain and associate the supply chain participants to the three main roots of complexity and uncertainty: the upstream/customer, the downstream/supplier, and the manufacturing/operations. Among the multiple PM models that have been proposed in the literature and that use different OR techniques, and considering the requirements settled for this work, simulation was deemed the most appropriate research technique. Particularly, hybrid simulation allows complying with the inherent system complexity, and anticipating the dynamic system behaviour under different circumstances. This reduces the need to compromise the modelling exercise, by using multiple modelling and simulation methods, which tackle the needs for enterprise wide solutions, not appropriately addressed by standalone simulation.

The use of different modelling and simulation methods allows addressing, in the same model and without falling in an unnatural representation of the processes, activities which are very different in nature (e.g. product development and production), but which are complementary, intertwined and highly relevant for the MTO/ETO value chains. These activities, which are modelled and simulated using different methods must be linked through events and other business rules, or shared variables, to ensure their connection. As an example, while the value chain is better captured by an ABS approach, the technical, conceptual and detailed design activity, given the reduced information available, and the high dynamism verified, is better captured by an SD model. The activities in the product realization stage are better captured by a DES approach, as long as information is available. If this is not verified, a simplified SD model can also capture, with a high level of abstraction, the activities in the product realization stage.

The hybrid models can be developed considering different designs for the interactions between models from different methods – interfaced, sequential, enrichment, and integrated – and the selection of the methods must consider their strengths in representing a given function, the intended model purposes and the data availability. As the implementation of a hybrid simulation model requires a great effort, the appropriate time must be devoted to understanding if the use of a hybrid simulation approach is justified. Though a rational approach has been pursued for selecting the methods that best fit each stage and activity of the MTO/ETO value chains, other modelling methods can be argued to be equally fit. This opens great room for discussion, as the selection of the modelling and simulation methods must be a direct outcome of the simulation requirements, e.g. the desired level of aggregation, and the information available about the system.

More than predicting the behaviour of the MTO/ETO low volume and high variety manufacturing environments across multidimensions, the H2PAM is a performance assessment tool that gives an estimate of the expected range of behaviour of the manufacturing system, aiding in comparing alternatives and, by using appropriate statistical tools and sensitivity analysis, identify opportunities for improvement. The H2PAM is an extremely flexible performance assessment framework that gives the modeler an openness to select the critical system components to be included in the analysis, through a system decomposition frame, and select the best modelling and simulation method to fit an intended purpose and information availability. Adding to this, the H2PAM is a multidimensional tool, which allows the simultaneous assessment of multiple key performance indicators. All these features are of critical relevance to the PM domain, as the majority of the existing PM frameworks lack a predictive/forward-looking approach, often focus on single dimensions of the performance measures, and often leave unconsidered some parts of the manufacturing system. This reduces their usability and applicability in real-world situations.

Two research outcomes have been settled at the outset of this work: defining a multidimensional performance assessment framework and establishing a roadmap for the selection of modelling and simulation methods for complex manufacturing environments. These outcomes have been accomplished through an extensive study of the MTO/ETO manufacturing value chains' literature and the application of the developed simulation models to real case studies.

This research work shows that a great deal of connection between the complexity concept and the mapping of the stages and activities in low volume manufacturing environments exists. This is a consequence of the inbuilt features of these manufacturing environments – impossibility of mapping one-to-one relationships, complex and multi-level products, constant interaction with customers during the product development, engineering revisions during manufacturing, complexity of the manufacturing processes, uniqueness of the jobs, complex interactions with suppliers – that make these manufacturing environments more complex and difficult to handle. Not only different project determinants are critical for the performance of MTO/ETO environments, including design/engineering workload, experience/knowledge of technology, complexity, outsourcing, design reuse, and project type; but also, the technical, conceptual and detailed design – product development – is the time bottleneck in these value chain processes, which enhances the relevance of considering its impact in the value chain.

Considering the above, it is easily perceived that tools that are used for high volume and low variety manufacturing environments cannot be applied in the MTO/ETO value chains. Only through the modelling of these systems, these can become more easily understandable. This calls for novel approaches that during the system domain understanding allow the concurrent consideration of processes which are very different but that are connected. Frameworks for the development of hybrid performance assessment models should be iterative and dynamic, answer key questions, build on previous knowledge to support the establishment of a strong literature, use a system decomposition frame, and consider the key constraints imposed by the system to be modelled (in this research work, the MTO/ETO value chain).

The research that has been presented throughout this work allowed to answer the two research questions that have been presented as the guiding lines of this work.

RQ1: *How can companies quantitatively predict the impact of key performance determinants on the MTO/ETO manufacturing environments future operational performance?*

Multiple PM models based on different OR methods have been proposed throughout time. Each approach has been shown by its proponents to have multiple advantages and drawbacks. Despite this, many authors have pointed to simulation approaches to solve more complex problems, yet at the cost of lower quality results, and difficulty (impossibility?) of generalizing the results obtained. Simulation has also been pointed as the primary method for achieving a forward-looking perspective during performance assessment, and "what-if?" analysis.

As the MTO/ETO value chains have been considered among the most complex, simulation arises as a good alternative to assess their performance. Indeed, standalone simulation approaches demonstrate to be insufficient. It is through a hybrid simulation approach that a proper mapping of these systems is possible, alongside a manageable system decomposition that maintains the integral analysis of a system. For this, a four-level structuring approach for the system decomposition, including the complexity levels value chain node, human or composed artefact, target acquisition, and target acquisition part, has been presented. It is through this decomposition that the foundation for the H2PAM is derived. By individually considering each of the value chain nodes, a more flexible mapping of the processes which are relevant for the system performance is achieved.

Answering the research question, companies operating in overly complex manufacturing environments can improve and predict their performance through a detailed mapping of their processes, and decomposition of the manufacturing system for modelling purposes, as long as the processes involved are known (even if with low levels of detail). A hybrid simulation approach allows achieving the needed flexibility for tackling the needs and constraints imposed by the MTO/ETO complex manufacturing environments. Modelling and simulation can, in this context, be used for predictive purposes, but most importantly, for insight achievement.

RQ2: *How to model and gain insight into complex MTO/ETO manufacturing environments? Which key processes should be included in the modelling exercise?*

The modelling and insight gaining about the processes involved in the MTO/ETO manufacturing value chains only become possible through the mapping of the stages and activities. The mapping process is in fact a key component of the modelling exercise. It is through the exploration of the features of these value chains that abstract models of the reality can be achieved and a better understanding of the systems becomes possible.

Obviously, models are always abstractions of reality, and no model can fully predict or describe the reality. Nevertheless, major approximations can be achieved when wider solutions are pursued. This means that upon identifying the key stages and activities in the MTO/ETO value chains (primary and support activities), none of these should be put aside and studied as being stable/fixed or inexistent. As all mapped functions are relevant for performance purposes, none should be left out of the analysis (as long as these are within the scope of analysis).

Following this, a roadmap for the selection of the appropriate simulation methods for each key stage and activity of the MTO/ETO value chains has been proposed. A great deal of discussion about the best-fitting methods for each activity has been presented in Chapter 3 – Research Methodology. Despite this, it is agreed that further arguments can be presented that support other methods best fitting the requirements of the modelled functions, than those that have been presented. It is settled that major trade-offs between the modelling objectives and data and information available about the systems exist. This represents a major opportunity to extend the work herein presented.

5.2. Research contributions

This work has major contributions to the academic literature and to practice, as conveyed by the proposed system decomposition frame, the roadmap for the selection of the best fit simulation methods for the MTO/ETO value chains, and, overall, by the H2PAM.

For the academic literature, the research contributions of this work are fourfold. First this work, by addressing the MTO/ETO value chains, which have been overlooked in the past, contributes to acquiring insight into these manufacturing environments, the mapping of their stages and activities, and their key performance determinants. Second, it contributes to the modelling and simulation literature, by proposing a novel performance assessment framework, built under the foundations of a hybrid simulation approach. This is particularly relevant given the absence of a defined framework for the selection of the appropriate simulation methods to be used in a hybrid approach. Third, this research work contributes to the performance measurement literature, by proposing the forward-looking H2PAM. Fourth, a set of papers have been published/submitted, that extends the literature, and presents solutions and new challenges for the scientific domain. Though not standing as one of the principal outcomes of this research work, the analysis of the OR quantitative techniques in Table 2.2, considering a set of requirements and corresponding criteria from the PM and MTO/ETO value chains domain, is relevant to demonstrate the value of a simulation approach, and point to its limitations.

This work also has practical contributions, as the different application studies demonstrate. Each of the explored studies had well defined purposes that show that the H2PAM can be applied to different types of MTO and ETO companies. While studies I and II focused on an advanced manufacturer of intralogistics solutions working on a combined MTO/ETO strategy, study III focused on the case of a major aerospace parts supplier, working under an MTO strategy. Studies I and II show a manufacturer that produces to order due to the high uncertainty in demand, that impedes it from storing an inventory of finished products. Adding to this, some of the manufactured products are made to the exact specifications of customers, meaning that these are only manufactured once. This highly contrasts with Cb, which produces to order, not due to the uncertainty in demand, but due to the inability to store finished components given their high monetary value and size. The fact that two different MTO/ETO manufacturers have been used as case studies, which are different in their working principles and operate in different business sectors, show the potential of the H2PAM to be applied to a great panoply of classes of MTO manufacturers. Despite this, the generalizability of the results obtained in this work is not possible, given the narrow range of application cases. This is a direct consequence of the research method/technique used: the simulation.

From a practical perspective, the H2PAM represents a set of models that can be used for the assessment of performance of MTO/ETO manufacturers. It can serve as a decision-support tool to aid operational managers in these companies making more informed decisions. Additionally, these models can be used for improving the companies' performance through the exploration of different working policies and improvement initiatives. Anticipating the consequences of actions becomes increasingly important, for which the use of closer to reality decision support tools gains widespread attention. Additionally, building models of operational processes can help to learn about the features of the manufacturing environments that would otherwise remain undiscovered.

5.3. Future research directions

By exploring the MTO/ETO value chains through a hybrid modelling and simulation approach, in the research presented in this thesis, an increased understanding about the key stages and activities for these manufacturing environments has been achieved. Despite this, many limitations, improvement opportunities and future research directions appear as a possibility.

The analysis presented in Table 2.2. is an empirical one. This table would benefit from refinement and many opportunities for enhancing the analysis presented can be considered. First and foremost, a bigger set of papers with models for PM, using the different quantitative OR techniques should be analysed, through a structured literature review. This has not been considered in the context of this work, as Table 2.2 served as a starting point to assess which would be the best research technique to tackle the requirements of highly complex and dynamic manufacturing environments. Notwithstanding this, after refining the contents of this table and the criteria established for the requirements, opportunities to create clusters of research techniques according to the requirements and criteria exist. This would be another important contribution to the PM models' literature.

Aligned with the limitations presented in Paper B, for the hybrid modelling and simulation literature review, we have restricted the analysis to papers focusing on the manufacturing and its business-related activities domain, which excluded important literature from the analysis. An extension of the literature review of hybrid simulation to other application domains would improve the understanding of hybrid simulation as a research tool, and the understanding of the frameworks for hybrid simulation.

The performance determinants identified in the literature have been associated with the hybrid model variables in study II (Papers D and E). Yet, the association between the determinants and the model variables has been a logical one, and not one built on the real system. For this, it becomes a priority finding evidence of the association between the performance determinants and the model variables affected by variations in the determinants. An appropriate mapping of these associations could be achieved through questionnaires sent to the manufacturing system experts.

Additionally, the application of the H2PAM to other case studies would improve the generalizability of the results obtained from the simulation models alongside proving that the models can be applied to a wide range of MTO/ETO manufacturers. This would enhance the relevance of the developed tools, adding to the contributions of the framework to the scientific and practical domains. Furthermore, and given the fact that the H2PAM has been applied to different types of MTO/ETO manufacturers, a need to develop a taxonomy for the classification of these companies exist. This taxonomy could be based on the different features of these companies and manufactured products, e.g. motivation for using an MTO strategy, type/variety of products manufactured. As for the model validation purposes, the face validity has only been applied to the model assumptions and inputs, it would be relevant to apply it to the model output. This would, however, be difficult as, for example, in Study III, the manufacturing system being evaluated only exists in one of the scenarios but does not exist in the remaining.

Many opportunities for improvement exist. First, the models have been implemented in a common platform (Anylogic), which some authors refer to as being less efficient and more difficult to modify (Wang et al., 2013a). It is a drawback of the implementation stage of the models, but which is justified by the easiness in the implementation. Yet, the models could be implemented in other dedicated platforms and comparisons could be made to determine if the less efficient model implementation in a common platform was indeed critical. Developing hybrid simulation models requires much time and dedication to the model development. For this, trade-offs between the model development time (and effort) should be weighed against the real possibilities presented by hybrid models.

To avoid running the model multiple times and increase the number of scenarios that can be analysed, metamodels of the simulation models (e.g. artificial neural networks, regression analysis) could be implemented. Complementary prediction tools, as machine learning algorithms, could heighten the results obtained. This shows that further developments in the proposed approach can be achieved through state-of-the-art techniques.

In the discussion in sub-sub-section 3.1.3. Roadmap for the development of hybrid MTO/ETO value chain models, some opportunities for improvement have also been referred, as the inclusion of a cost control feedback loop, to avoid deviations to the expected calculated cost; the explicit modelling of the procurement activity, which has been simulated as a simple delay; and considering other planning alternatives. From the production perspective, the planning function could be improved by the implementation of optimization algorithms. Hence, the performance of the hybrid simulation model could be enriched by becoming a simulation-optimization approach. The proposed hybrid simulation model could be extended by considering competing MTO/ETO manufacturers, which would improve the representation of the quotation and tendering stages in the value chain. Another important consideration in the developed hybrid models is that for the technical, conceptual and detailed design, SD models have been used. However, this constrains the representation of the heterogeneity among the product components, which is not considered in these models. For this, average values have been considered, which may deviate the results from reality. To include heterogeneity in the models, array variables can be included in the SD models, following an enrichment model design.

Future work should also explore the development of a set of guidelines (framework) for the selection of the most appropriate simulation methods for a given manufacturing function. This framework should extend the roadmap proposed in sub-sub-section 3.1.3. Roadmap for the development of hybrid MTO/ETO value chain models.

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Appendices – collection of published papers

In the appendices section is presented the integral body text of all papers that have been produced/published in the context of the thesis.

Paper A

Evaluation of improvement actions impact on manufacturing operational performance

Cátia Barbosa, Américo Azevedo

The Version of Record of this manuscript has been published and is available in IEEE
Explore, 2015, https://ieeexplore.ieee.org/document/7385790/

Abstract – Due to the current demands from the market, technological improvements and action of competitors, manufacturing companies are pushed to compete in shorter product development cycles. This poses a great challenge, as the conventional product development cycle is shortened. Hence, companies are forced to introduce some improvement action plans and adopt certain manufacturing operational strategies to remain competitive and achieve a good market share. Due to the importance of this topic, in this paper we revise the current manufacturing improvement plans in the literature, to establish the basis of our future research work. The findings of this work point towards the need to develop a system that integrates the evaluation of the manufacturing improvement plans in the future overall performance of the manufacturing plant and aid in the process of decision-making.

Keywords - Complexity, Manufacturing, Performance, Product life cycle

I. Introduction

Currently, organizations are receiving a higher push to offer products that more reliable, with more features, at lower prices [1], and a larger product portfolio [2]. The users' needs are the drivers for product design and manufacturing. However, due to differences among users, it becomes necessary to create a great variety of products [3]. The increased product variety as demanded by the market is one of the main drivers of manufacturing complexity [2, 4].

Complex manufacturing systems are difficult to define [5]. The complexity of manufacturing systems appears under a variety of aspects [6], and resides in the high number of parts that constitute these systems, as well as the rarely simple relationships amongst these parts [5]. The complexity of the manufacturing systems results from the great number of products, the variability in the product mix, the multiplicity of involved processes, and the actions from external agents [7]. In fact, the high complexity in manufacturing systems is a consequence of the social and technical systems interaction [8].

There are three main variants that were identified in the literature as the origin of manufacturing systems complexity: product, processes and operations and systems [9-11]. The linkage among parts in a manufacturing system affects complexity. The more complicated the products, processes and manufacturing systems, the higher is the cost of design, implementation, planning, operations and control. Therefore, it is needed a trade-off between simplicity and complexity and the effects on competitiveness and profits [12]. Industries as electronics, semiconductor, aerospace and automotive are highly complex [13].

The fast technology development and the high competition among companies lead to reduced product life cycles. Hence, companies face the challenge of adapting and creating an effective planning for their facilities to be useful for a period of time longer than the life cycle of the individual products they are producing [14]. The reduced product life cycles tend to increase the importance of competing in the product development cycle time [15]. Therefore time-to-market appears as a crucial competitive factor for companies through all markets. Companies achieving shorter product development cycles can achieve higher market share. and profits [16]. The framework in Fig.1 summarizes these interactions of the manufacturing companies, markets, competitors and internal actions.

Considering that the manufacturing environment is rapidly and constantly changing, with higher levels of customization and complexity, there is higher demand for flexibility and adaptability from companies [17, 18]. Flexibility in manufacturing systems provides advantages as higher product quality, reduced lead times, and reduced work-in-progress, among others [19].

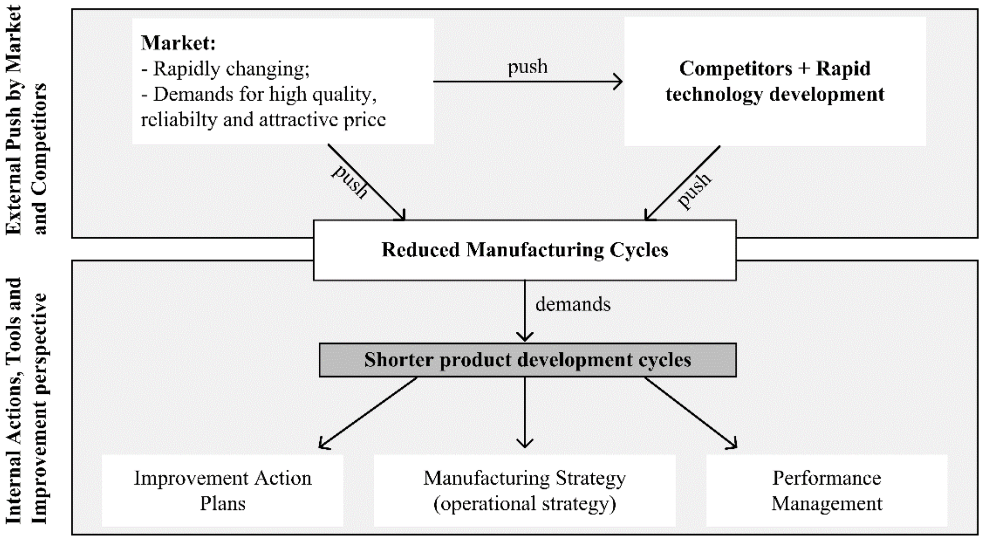

Fig. 1. Framework for the interactions of the manufacturing companies, markets, competitors and internal actions.

The conventional life cycle of a product is divided in four stages: introduction, growth, maturity and decline. Sales are very much reduced in the introduction stage; when the investments are paid, the product moves to the growth stage; when there is a slowdown in sales, the product enters in the maturity phase, and finally ends in the decline stage, with a possible sales decrease [20]. With the reduced product's life cycle, the product life cycle curve has to move to right, as in Fig.2, meaning that the time to introduce a product to the market and develop it is much more reduced, and the slow-growing curve slope of introduction and growth stages has to be much higher, so the product achieve acceptable sales faster.

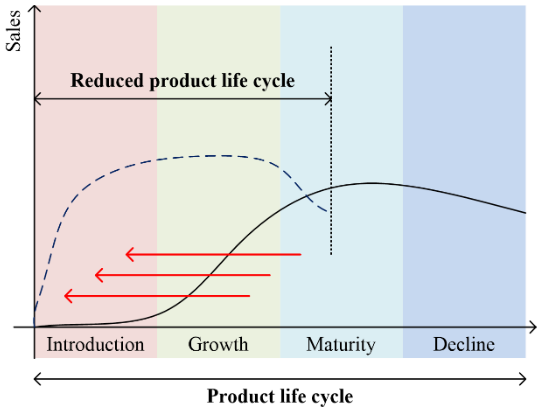

Fig. 2. Conventional product life cycle and reduced product life cycle, as demanded by markets and technological development.

This poses a major question regarding the methodologies, tools and strategies that are being employed by companies to evaluate the performance impact of their improvement actions in the manufacturing environment. Hence, our future research question is:

RQ: How can companies assess the effect of operational strategies (e.g. action plans) on future operational performance?

At this preliminary stage of our study, we aim at understanding the main practices and tools that have been used throughout time to manage the reduction in the product's life cycle and the impact of those strategies in the manufacturing plant. To achieve this, we performed a literature research, using important scientific databases (e.g. Scopus, Science Direct, Emerald Insight, Taylor & Francis Online, among others).

The remaining of the paper is organized as follows. Section II includes a review about manufacturing improvement actions that have been reported in literature and their impact in the manufacturing plant; and section III provides the most important conclusions retrieved from the literature research and the future research directions we will be following in the future.

II. Improvement Actions and Impact on the Manufacturing Plant

It is very difficult to predict the effects that decisions and actions in the manufacturing environment, will have in the future systems performance. This is due to the dynamism in manufacturing that increases the number of decisions that need to be made [8]. Good manufacturing systems performance is highly dependent on an efficient design, planning and scheduling on a real-time running system [21].

Organizations achieve their goals by satisfying their customers more effectively and more efficiently than their competitors. For this, the performance level of an organization is a function of efficiency and effectiveness of the actions it adopts [22]. The speed, flexibility and quality with which a company serves its customers, measured against the capacity to balance the demand, the manufacturing capacity and the supply, gives the performance of a manufacturing organization. By modelling the system dynamics, the operation of the manufacturing facility can be understood and simplified, and waste in the process can be eliminated [2].

Performance indicators for manufacturing systems are unpredictable. In [23], the authors identified a set of four manufacturing performance indicators: cost, time, quality and flexibility. The authors proposed a method to analyze the complexity of a manufacturing system, considering the unpredictable nature of the performance indicators. The unpredictable behaviour of the performance indicators was analysed from a time series perspective, using the complexity measure of the Kolmogorov Lempel Ziv.

The design of flexible manufacturing systems is very complex. It must consider many criteria, as cost, production, flexibility, among others. Taking this into consideration, Borenstein, Becker and Santos [24] proposed a method to analyze the flexible manufacturing systems design, using integrated, systemic, global and user-centered approach. This approach introduced a successful method to incorporate the company's strategy during the stage of design of flexible manufacturing systems. Additionally, in [25] was presented a framework methodology to develop complex flexible manufacturing systems, including the simulation of system behaviour.

Industrial enterprises face the challenge to deal with complexity and uncertainty, being manufacturing strategy of major importance to cope with these [26]. However, the manufacturing strategy formation is a very complex process that needs to consider deliberate and emergent decisions and actions [27]. Due to the uncertainty generated by complexity, several authors have claimed that complexity reduction should be one of the goals of operations [19, 28], as less complex systems have proved to be more efficient and robust, and because productivity drops as systems become more complex [10, 19].

Some common initiatives were taken for enhancement of manufacturing processes. Some examples of these initiatives include: 5S, lean thinking, Six Sigma, total quality management [1], zero defects, just-in-time, manufacturing lead time reduction [29]. However, the impact of these manufacturing practices has not been clearly understood, and a study [29] showed that there is not a straightforward relationship amongst manufacturing improvement programs and actions and manufacturing performance.

Nowadays it is very important that firms are able to organize their performance management. For companies engaged in a continuous improvement philosophy, a very common tool to be used is the PDCA (Plan-Do-Check-Act) cycle, first introduced by Deming. In [30] the authors concluded that the PDCA cycle can be an effective tool to better manage performance.

Furthermore, Berrah, Mauris and Montmain [31] considered the few quantitative approaches in literature of Performance Measurement Systems (PMSs) as a motive to further develop a model using a Choquet integral aggregation operator. Their proposed model intended the monitoring of the continuous improvement action plans, to help managers to continuously improve the performance of their firms, as well as more effectively distribute resources to achieve a desired level of performance.

When conducting a study on the data retrieved from the third International Manufacturing Strategy Survey, the authors in [32] found that companies that had an official manufacturing strategy with clearly defined competitive priorities, improvement action plans and programs where much better aligned than those companies that did not present a clear strategy. Companies that clearly establish a manufacturing strategy are more successful in translating competitive priorities in manufacturing improvement and action programs. The manufacturing strategy is usually more or less formally defined; however, some decisions performed by managers are emergent. Even though the translation of competitive priorities into improvement programs is successful for companies with a defined manufacturing strategy, those manufacturing action programs also limit competitive priorities.

Delayed product differentiation has been pointed as a means of reducing manufacturing complexity and accomplishing competitive advantage in the market. This included the postponing of the stages at which product varieties and differentiation appeared in the manufacturing systems [4].

In order to understand customers' satisfaction level and areas in the organization with room for improvement, Yang [33] used customers' satisfaction survey. Continuous improvement actions were found to make possible the increase in customers' satisfaction and profits. The author claimed that with the information retrieved from the customers' satisfaction survey and by deducing and using an optimization theory inside a company, it becomes possible the focusing on optimal conditions and identification of the critical attributes that need to be improved.

Kim and Arnold [34] developed a model for manufacturing strategy development in order to connect the competitive priorities of the organization with the decisions and action programs that have to be developed. It was observed that when a company had its competitive priorities focused on a determined goal, manufacturing objectives and action plans were pointed to a certain direction, to meet that goal.

It is very important that companies identify their improvement priorities. For this reason, Barad and Gien [35] developed a framework to aid in determining the improvement priorities of small and medium enterprises, by approaching a process very similar to the manufacturing strategy formation. The authors proposed the successful use of quality function deployment in their framework to understand the needs from customers and translate those needs into improvement targets.

Assuming that the best performing companies are those that employ the best manufacturing practices, in [36] was performed a study on the highest performing firms of the 2002 International Manufacturing Strategy Survey database to identify those best practices. On one hand, the best practices that were identified corresponded to the high focus on the process, pull production, the productivity of equipment and environmental concerns. On the other hand, quality management was found not to be very relevant amongst the best manufacturing practices.

The study performed by Swink, Narasimhan and Kim [37] advanced the theory that practices affect performance through the integration of strategy and manufacturing capabilities as cost and flexibility. Their conclusions state that when integrating strategy there is more efficiency in terms of cost and product flexibility. Additionally, the integration of strategy allows better development of products and processes, supplier relationship, workforce growth, just-in-time flow, among others.

III. Conclusions and Future Research Directions

The contribution of this paper to the literature of the improvement actions performed in the context of manufacturing companies resides in the gathering of information regarding recurrent improvement practices and plans employed by managers. This is particularly relevant because different improvement have very different results on the complex manufacturing systems performance.

Amongst the commonly referred actions to improve manufacturing performance are: the alignment of actions in the manufacturing plant with competitive priorities, the continuous improvement actions, quality function deployment, environmental concerns, the delayed product differentiation, lean manufacturing, and the PDCA cycle.

Manufacturing strategy is very complex and dependent on several factors. This is a consequence of the volatility of expectations and demands from the market and from the constantly improving technology and actions performed by the competitors. Moreover, the fact that the manufacturing plant needs to be constantly adapting to the new requirements induced by the introduction of new products and product variants, adds the need for flexibility. One of the strategies that have been pointed as a good mean of controlling the systems actions is the modelling of system dynamics.

There is high unpredictability in performance indicators on manufacturing companies. Hence, the degree of difficulty in accurately understanding the impact that manufacturing decisions and improvement plans have on performance is aggravated.

As it would be expected, all the decisions performed in the manufacturing companies influence the level of performance achieved. As it is very difficult to understand the impact that certain decisions have on the future performance, it becomes even harder to make the necessary decisions with safety. Even though some works have been found in literature focusing on the impact that manufacturing choices and complexity have on the plant performance, this research area appears as still having great room for improvement, especially in what concerns to understanding the impact that product complexity has on performance, or predicting the success or failure of a product; but also in understanding the impact that the operations strategy and the processing environment have on the overall performance.

One of the drawbacks we found on the currently available literature resides in the lack of practical application of the frameworks developed by the authors and their consequent performance evaluation. This opens a research branch to be explored, with the need to proceed to the real application of the theoretical frameworks, to better understand their effectiveness and value.

Our future research directions are pointed towards answering the research question introduced in this paper. To achieve our goal, we plan on using a hybrid approach, with qualitative and quantitative methods. This will allow the evaluation of the operational choices in the real manufacturing environment, and the quantification of the impact that those choices have in the overall performance. The qualitative evaluation of the system will make use of case studies in complex manufacturing systems, which will allow an understanding the most recurrent operational actions performed in these environments. The quantitative part of the method to be developed will make use of the modelling of the system's dynamics, to better understand the nonlinear behaviour of the systems. However, the system dynamics looks at the system with a very broad perspective. To overcome this shortcoming, we intend on also using agent-based modelling to better understand the complexity of the interactions developed among agents in the manufacturing environment. Discrete event simulation will also be used to have an insight about the most relevant alterations that occur in the system from one event to the other. Other tools might as well be useful during the project, as neural networks or support vector machines. This tool we intend on developing will allow managers to act faster and more efficiently. Fig. 3 shows the framework to be followed in the current work development.

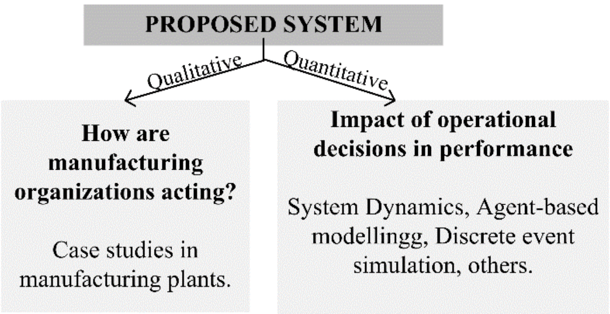

Fig. 3. Framework that serves as guide in the work to be developed.

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Paper B

Hybrid Simulation for Complex Manufacturing Value-chain Environments

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Abstract - Hybrid simulation is nowadays a valid alternative for studying complex manufacturing environments. Some challenges exist in this context, as the ambiguous use of terms and definitions in the literature; and the demanding skills required for developing hybrid models. A structured literature review provides an overview of the use of hybrid simulation in manufacturing business performance and its most important advantages and drawbacks. A classification scheme for the 51 analysed papers is presented, including interfaced, sequential, enrichment, and integrated taxonomies.

Keywords - Agent-Based Simulation; Discrete Event Simulation; Hybrid Simulation; Manufacturing; System Dynamics; Taxonomy

1. Introduction

The complexity of modern manufacturing systems and the interactions in this context demand the use of simulation as an alternative to cumbersome mathematical models [1, 2]. Simulation is one of the most commonly used techniques in Operational Research (OR) [3]. It is very popular for modelling complex manufacturing systems [4, 5], assessing the impact of decisions [6], optimizing designs and operations, and assessing performance [7, 8]. There are many benefits in using simulation, as early insights on the behaviour of complex systems [4], flexibility [2, 9], cost efficiency [10], easy development [2], few simplifying assumptions to the models [9], scaling-up of the models, quick running times, analysis of “what-if” scenarios, and ethical experimentation [2].

Recent demands from global business optimization, human decision making, and complexity of modern systems, push researchers for using hybrid simulation approaches, combining different simulation methods, for better understanding of complex interactions between processes of different nature [3, 8]. Adopting the definition in [3], hybrid approaches are those combining at least two of three simulation methods – System Dynamics (SD), Discrete Event Simulation (DES), and Agent Based Simulation (ABS).

Albeit there is a growing interest in hybrid simulation approaches, many questions remain unsolved. There is no unified use of terms and definitions in the literature [11], which introduces ambiguity. Literature in hybrid simulation is sparse, hampering the work of researchers interested in the topic. Also, many challenges arise when using more than one simulation method, as establishing information sharing between the models [12], converting time units [12, 13], and the skills required for building the models [14].

This work aims at providing insight on the use of hybrid simulation in manufacturing business performance; and the most important advantages and challenges of using hybrid simulation. We try to answer two research questions:

RQ1: Where and how has hybrid simulation been used in the context of manufacturing business performance analysis?

RQ2: Which are the key aspects and challenges for hybrid simulation approaches?

Particularly, focus is laid on exploring the different designs of hybrid simulation approaches which have been published in the context of manufacturing business performance (e.g. manufacturing supply chain, logistics), by following a structured literature review, focusing on the different combinations of methods (SD-DES, DES-ABS, SD-ABS, others). Furthermore, and focusing on the second research question, the key issues modelers should focus on when developing hybrid simulation models are explored.

The remaining of the paper is organized as follows. Section 2 includes a description of the three simulation methods. Section 3 highlights the steps in the structured literature review, the classification scheme for the different design approaches to hybrid simulation in the literature, and the challenges of hybrid simulation; and section 4 concludes the paper and provides guidance for future research.

2. Simulation methods

2.1. System Dynamics (SD)

SD was developed at the MIT, in the 1950s, by Jay W. Forrester [15, 16], and was initially called Industrial Dynamics [16]. It is a systems thinking approach [9], focusing on an aggregate view of the systems and emphasizes feedback mechanisms and their endogenous nature [12]. In SD, the structure of the real world determines behaviour over time [12, 15]. The endogenous behaviour results from feedback loops [16] creating dynamic complexity [17].

Processes are represented by stocks, flows between the stocks and feedback loops (balancing and reinforcing). SD focuses on policies instead of single events. All elements which influence the behaviour of the system have to be modelled endogenously [16]. SD models use finite differential equations to capture interactions between subsystems and the impact of delays [6]. Models are qualitative and quantitative: the qualitative aspect is related to developing the causal loop diagrams through discussion; variables must be quantified and the quantitative SD is used through stock-flow models. SD models are deterministic and do not require multiple iterations [15]. It is a “continuous” simulation method, in which time advances in small constant steps [18].

It is very important for understanding complex systems [19], in which time is an important factor [7]. It was primarily applied to supply chains (SCs), and later to economics, ecology, innovation, workforce management, software development, competition, and markets [17]. SD is adequate for representing the management environment, enabling practitioners to analyse strategic planning scenarios and simulation policies and operations [7]. Nonetheless, due to the continuous nature of SD, it is not capable of mapping discrete events which are common in many industries [20]. For a more comprehensive view of SD, please refer to Sterman [21].

2.2. Discrete Event Simulation (DES)

DES dates back to the 1960s; it was introduced by Geoffrey Gordon in its idea for General Purpose Simulation System (GPSS) [22]. It is the most commonly used simulation method in manufacturing, for evaluating planning, routing and scheduling alternatives [9]. Modelling occurs from a macroscopic point of view [8]. The most important elements in DES are entities, activities, resources, queues, and events [19]. Entities are passive objects which may represent messages, tasks, and people; these entities travel through blocks of activities where they stay in queues, suffer delays, are processed, seize and release resources [22]. State variables change in discrete points in time, called events [15, 18]. Models require accurate data or accurate estimates on system’s operation [1].

There are two world-views in DES: process-oriented and event-oriented [15]. In the process-oriented worldview, entities move through various processes, and each process requires resources and a certain amount of time for completion. Entities do not have a defined behaviour and are purely data containers. The flow of entities through the system is governed by rules assigned to system (probabilistic or condition-based), and not by a decision process internal to the entities. In the event-oriented worldview, the events are themselves the primary modelling element.

DES has been widely used at the operational level of organizations, for modelling production [20], and studying the system behaviour in response to detailed events in discrete points in time [5]. It is widely used for productivity analysis in manufacturing [13, 23], and logistics [24]. This method is particularly useful for problems with queueing simulations and variability is represented through stochastic distributions. DES models have a process oriented approach and are based on top-down modelling [24]. In spite of being a well-established method, DES does not address the stability of the system, which is very important when analysing the system in an aggregated level of planning [19]. More detailed information about DES can be found in [25].

2.3. Agent-Based Simulation (ABS)

ABS is a more recent method [15], whose definitions are not yet universally accepted. There is a wide discussion referring to the properties that an object should have in order to be called an agent [22]. It adopts a bottom-up, microscopic approach, in which agents exhibit behaviour at the individual level [8, 26]. Agents live together in a certain environment, communicating with each other and with the environment, according to a number of logic rules. The macro-level behaviour of the system results from the individual interactions among agents [8]. It is possible to assess how agent diversity affects emergent behaviours of the system as a whole [15].

Agent's properties documented throughout time include proactiveness, purposefulness, situatedness, reactiveness, responsiveness, autonomy, social ability, anthromorphity, learning, continuity, mobility, and specific purpose. Agents can represent entities in a system, as human beings, animals, or institutions [16]. An agent's internal state is dynamic and changes as the agent's experiences accumulate and are recorded in memory [15].

ABS is increasingly used in business related areas, as manufacturing, maintenance and SC management [17]. As many details as possible are used to represent the individual features of the different elements of the system [12]. This is supported by the increased number of available databases and computational power, which allow micro simulations [17]. It is suitable for modelling adaptive and dynamic manufacturing systems [4]. Data requirements are high and often data collection may be difficult, e.g. when collecting data about human behaviour [23].

3. Hybrid simulation approaches – a literature review

This review reports publications targeting hybrid simulations in manufacturing business performance. To make the review as comprehensive as possible, the publication year was not restricted, which resulted in a span of publications across more than 30 years. The literature review followed a structured approach, based on the work by Jahangirian et al. [27], and adopted the steps in Fig.1.

The keywords' selection considered the dispersion of terms in the literature [11].; these included "manufacturing", "multi-method simulation", "hybrid simulation", "multi-paradigm simulation", "combined simulation". Three scientific databases were used: Scopus, Science Direct and Emerald Insight.

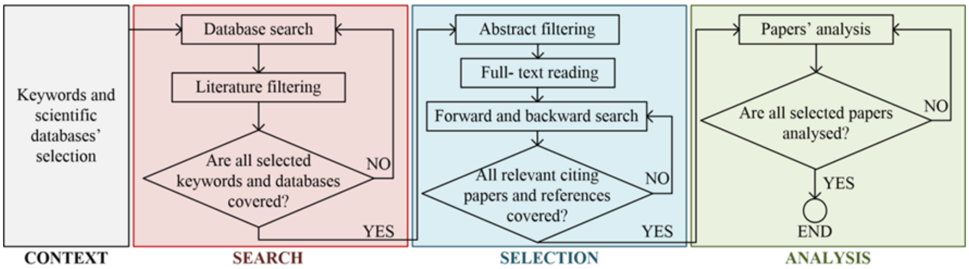

Fig. 1. Structured literature review approach.

Literature filtering included elimination of duplicates, non-English papers and unavailable papers. The following step included reading the abstract of all filtered papers. For a paper to be selected, it had to be explicit that more than one simulation method was used and that the context of the simulations was in manufacturing business. All papers selected based on the abstract were fully read and a backward and forward search (references and citing papers) were conducted to increase the range of papers. A total of 51 papers were fully analysed, distributed across different publication years. Database search was performed amid September and October 2016. Due to the space restrictions, only a part of the search results is presented in this work.

3.1. Classification scheme for the hybrid simulation approaches

Hybrid simulation approaches not only differ in model inputs, objectives and outputs, but also in the design of the simulation models, with different relationships between models from different methods. A taxonomy of classifications for the design of hybrid simulation models, based on the classification scheme proposed by Swinerd and McNaught [3] for hybridism using SD and ABS, is presented. The classification scheme is extended to all combinations of methods; and adding the enrichment taxonomy as presented by Morgan, Howick and

Belton [28]. There are four taxonomies in the classification scheme: interfaced, sequential, enrichment, and integrated, as in Fig. 2:

- Interfaced (Fig. 2(a)) – Models from different methods are individually applied, and are uncoupled. There is comparison of results at specific points in time to discover opportunities of complementarity and compatibility.
- Sequential ((Fig. 2(b)) - Methods operate separately, one method follows the other, and methods are uncoupled but dependent and complementary. Results from the previous method are used in the following method.
- Enrichment ((Fig. 2(c)) - A single method is used, which is enriched with principles from other method(s).
- Integrated ((Fig. 2(d)) – Models from different methods are fully coupled. There is constant exchange of information and feedback mechanisms in more than one point in time between models from different methods.

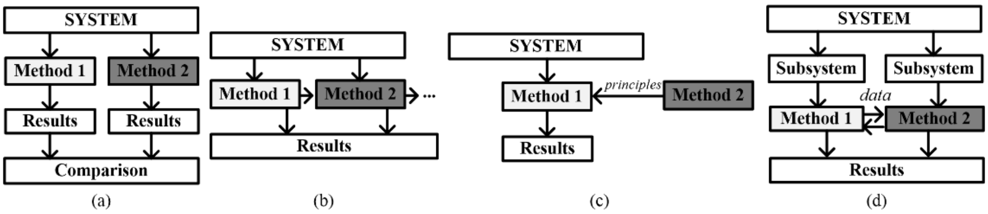

Fig. 2. Taxonomies in the classification scheme for the hybrid simulations. (a) Interfaced (adapted from [3]); (b) Sequential (adapted from [3]); (c) Enrichment (adapted from [28]); (d) Integrated (adapted from [3]).

3.2. Results from structured literature review

A total of 51 papers covering hybrid simulation approaches have been analysed. Among these, 7 were in the interfaced taxonomy, 7 in the sequential taxonomy, 6 in the enrichment taxonomy and 31 in the integrated taxonomy. In the interfaced taxonomy, models developed using different methods have the least interaction. Model outputs are compared in [26, 29-33] for assessing which modelling and simulation method best suits a particular part of the system In [29], the authors simulated a JIT/Kanban manufacturing process using SD and DES, and compared the obtained results; a similar approach was used in [30], but for studying a production line operating under constant work in process. Parunak et al. [33] developed agents and equations models for supply networks, and in [26], Demirel compares the capabilities of supply chain models built using SD and ABS. A different approach was used in [31], where the authors used systems thinking techniques within the context of DES, for capital investment decisions. Alternatively, guidelines for the integration of the models are presented in [34]. In the sequential approach, there are two lines of research. In the first, the authors start by selecting one method for modelling the system; however, these later realise the need of using another method for better analysis [35, 36]. In the second line of research, one of the methods is first used for developing a model; its’ output results are then passed to a second model built using a different method, and often with different level of detail. In this approach, there may be feedback mechanisms, but the models are not simultaneously executed (e.g. in [37]). Different problems have been explored in the sequential approaches, as safety and productivity evaluation in manufacturing layouts [23], software project planning and management [35], evaluation and improvement of supply chain processes [38], assessment of green logistics practices in the automotive industry [37], evaluation of energy trade-offs in the supply chain [39], and production planning [36, 40].

Enrichment entails the use of principles of one method into other method. In some approaches, the authors use a software which is typical for one method, but applying principles [41, 42], or libraries [43] of other method. The realm of target problems in the enrichment taxonomy includes policies for managing job shop [41], warehouse operations [43], supply networks [44], and colliery operations [45]. The integrated taxonomy is the most commonly used in literature. A wide realm of problems has been addressed in the literature using this approach, including hierarchical problems [5, 46, 47], operational processes and SC phenomena [7, 48-50], enterprise simulation [6, 9, 20, 51-54], value chain analysis [55], agile manufacturing [56], material handling systems [4], SC management [57]. Regardless the topics under study, models in this taxonomy have feedback mechanisms and the models from different simulation methods are executed simultaneously. Table 1shows the results of the structured literature review, with the assignment of the papers to the different taxonomies.

Table 1. Results from the structured literature review

Taxonomy	**Methods**			**References**	**Taxonomy**	**Methods**			**References**
	SD	**DES**	**ABS**			**SD**	**DES**	**ABS**	
Interfaced	●	●		[29-32]	Enrichment		●	●	[41, 43]
	●		●	[26, 33, 34]		●		●	[42, 44, 45, 58]
Sequential	●	●		[35-38, 40]	Integrated	●	●		[5-7, 9, 20, 46-55, 59, 60]
		●	●	[23]			●	●	[4, 8, 24, 56, 61-63]
	●	●	●	[39]		●		●	[12, 57, 64-66]
						●	●	●	[67, 68]

3.3. Aspects and challenges of hybrid simulation approaches

When developing a simulation, the method is chosen depending on the structure of the system and the objectives of the simulation [63]. It can be extremely time consuming developing models of complex systems using standalone simulation methods [63, 69]. In this situation, there is the need to use a hybrid approach [63]. Even though hybrid simulation approaches are more and more frequent, the combination of two methods only is justified when the developed models are of equal importance to the overall goal of the simulation [20]. In fact, combining models from different methods requires much effort and precision to establish which information should be shared and how often it should be shared [12]. Some common problems which arise in hybrid simulations and are not relevant in standalone simulation include the different time units in the models. Time units have to be converted so that proper data exchange is feasible and inconsistencies avoided [12, 13]. Also, developing hybrid models requires much knowledge about different simulation methods, high skills and flexibility from practitioners to find a good fit between models [14]. Choosing the appropriate methods to use is also a great challenge for hybrid simulations [11].

Despite the high demands of hybrid simulation, when its use is justified, many advantages can be achieved. One of the great benefits of hybrid simulation is flexibility [68]. The challenge of simulating a complex system using standalone simulation is overcome [63] and extracting the best features of the selected methods becomes possible [19]. It is possible to simulate different levels of aggregation when models using different methods are combined [12]; also, combining these models allows conjoint analysis of results, avoiding problems of model consistency, redundancy of components, model investigation effort [59]. Some of the purposes of hybridism include complementarity of the methods used [1, 11], coupling between methods, exploration of multilateral problems, stakeholder acceptability, need for a unique representation, validity, data availability and usability, expectation of unique insight, dimensions, and criteria [11]. Models combining discrete and continuous variables are convenient for explaining the dynamic behaviour of systems, confirming the validity of alterations to the system, predicting system behaviour, benchmarking competitive improvement strategies, checking novel adaptive control systems, and approximating a discretely changing variable using continuously changing variables [70, 71].

4. Conclusions and future research directions

Two important problems of the realm of hybrid simulation have been explored. The first was related to the lack of agreement in the terms used by different researchers, which introduces some misperceptions. A structured review was conducted, using different keyword combinations, to gather as much information as possible about hybrid simulation design in manufacturing business performance; aiding researchers in finding appropriate literature. A classification scheme allows understanding the different approaches to hybrid simulation design which have been used in the literature. The second problem included summarizing some key aspects and challenges of hybrid simulation.

Even though comprehensive, the review approach may exclude some relevant works. A broader range of databases should be used, and the scope of the review enlarged, so that other areas (e.g. healthcare, construction) may be included in the review. Furthermore, better inclusion criteria in the different taxonomies should be provided.

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Paper C

Hybrid modelling of MTO/ETO manufacturing environments for performance assessment

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Abstract - Performance assessment is critical in today's competitive environments, where companies need to establish trade-offs between key competitive dimensions. The complexity of these environments calls for new approaches to performance assessment. Thus, in this work, we propose a novel conceptual framework for performance assessment in manufacturing environments combining different production strategies. Focus is laid on MTO/ETO combined environments and a three-stage problem analysis is considered. Firstly, a hybrid SD-DES-ABS model approach addresses the needs of a system that handles different types of orders, processes and workforce allocation requirements; secondly, the model results for different demand scenarios are assessed using a one-way ANOVA analysis followed by a Tukey – Kramer's test, with pairwise comparisons for assessment of significant performance variations under different system operating policies. A full factorial Design of Experiments (DOE) analysis follows, for determining the relevant process parameters influencing the system performance. As an example of application of the proposed framework, we consider the case of an advanced manufacturing company, whose manufacturing environment encompasses combined MTO/ETO production strategies.

Keywords - ANOVA; design of experiments; engineer-to-order; hybrid simulation; make-to-order

Introduction

Modern manufacturing organizations are subject to high business pressures, including globalization, market competition (Nudurupati et al. 2011), customer demand for customized, sophisticated, high-quality and innovative products (Chen 2008), shorter product's life cycles and increasingly complex production processes. These organizations must properly implement and manage operations strategies and improvement actions to remain competitive and satisfy customers efficiently and effectively. Hence, performance assessment is critical for challenging strategic choices and reviewing objectives as market circumstances change (Neely, Gregory, and Platts 1995).

Good performance of manufacturing organizations depends on dimensions as cost, response time, efficiency, service levels, and quality of products and services. Establishing trade-offs among these entails competing in different positions of the spectrum between make-to-stock (MTS) and engineer-to-order (ETO) strategies, often resulting in combined strategies. The customer order decoupling point (CODP) reserves different products for customers with different requirements (Akinc and Meredith 2015). There is usually a dominant CODP (van Donk and van Doorne 2016) and its positioning reflects the company's strategic choice: make-to-stock (MTS), assemble-to-order (ATO), MTO and ETO (Rudberg and Wikner 2004).

In MTS, product specifications are set long before the customer makes the decision of ordering the products. Products are simple, with focus on productivity, operations, and costs. Although companies operate under uncertainty, using demand forecasts, and with risk of product obsolescence, the MTS strategy is appealing due to the high capacity utilisation and short lead times (Rafiei and Rabbani 2011). For companies following an ATO strategy, pre-manufactured components are assembled to the customers' specifications, when the customer order arrives. A MTO strategy includes configuring the products following a set of pre-defined attributes, and production according to a selected configuration; the customer chooses the product according to limited available options (Willner et al. 2014). MTO companies respond to deterministic demand, but are more vulnerable to disturbances, as disruptions in material supplies and demand variation. These operate with longer lead times and large order backlogs (Rafiei and Rabbani 2011). ETO manufacturers provide unique and complex products. These manufacturers must be flexible, providing products to the specific customers' needs, and manufacturing in small quantities (Rudberg and Wikner 2004). Manufacturing the product is part of the manufacturing project and large cost penalties are imposed by customers for lateness.

For a manufacturing organization, the CODP may vary between products offered, or over time, resulting in combined production strategies. Manufacturing environments combining different production and operations strategies are very complex, involving several processes and resources, and a variety of problems that may arise. This calls for using different methods to analyse different problems in the same production environment. The hybrid MTS/MTO combined strategies is one of the most dominant production strategies, drawing attention of academics and practitioners (Rafiei, Rabbani, and Alimardani 2013). On the contrary, as Hendry (2010) identified, MTO/ETO has received little attention in the literature. Only recently, due to the pressure that manufacturing companies have had to offer more customized products, and in search for more agility and flexibility (Grabenstetter and Usher 2014), attention has focused on MTO (Stevenson, Hendry, and Kingsman 2005) and ETO (Grabenstetter and Usher 2014) strategies. As engineering and production activities are core in MTO and ETO, an integrated approach, considering the influence of both activities in performance is needed. Hence, in this work, we focus on combined MTO/ETO operations environment.

Simulation modelling often arises as an alternative to quantitative models approaches for analysing complex manufacturing systems, particularly when time dynamics is important (Borshchev and Filippov 2004). It allows modelling systems, aiding in decision-making, and performance assessment (Umeda and Zhang 2008). Hybrid simulation approaches result from the increased complexity of manufacturing systems, which require different methods for analysing different problems. These approaches combine at least two of three simulation methods - System Dynamics (SD), Discrete Event Simulation (DES), and Agent Based Simulation (ABS) (Swinerd and McNaught 2012).

Considering the complexity of manufacturing systems combining different production strategies, and the capabilities of hybrid simulation in capturing the interactions among processes of different nature, we propose a novel conceptual framework for modelling and assessing performance of manufacturing environments where different production strategies co-exist. The framework focuses on MTO/ETO combined environments and considers a three-stage problem analysis. Firstly, a hybrid SD-DES-ABS approach addresses the needs of a system that handles different types of orders, processes and workforce allocation requirements; secondly, the model results for different demand scenarios are assessed using a one-way ANOVA analysis followed by a Tukey – Kramer's test, with pairwise comparisons for assessment of significant performance variations under different system operating policies. A full factorial Design of Experiments (DOE) analysis follows, for determining the relevant process parameters influencing the system performance. The proposed framework was applied to the case of an advanced manufacturing company, operating in a combined MTO/ETO strategy.

The remaining of the paper is organized as follows. Section 2 provides a literature overview of the topics relevant in the context of this work. Section 3 delves on the proposed modelling architecture, capturing the different modules in the system, and the model assumptions. Section 4 explores the case study company, and a justification for the company's selection for the application of the developed model; section 5 explores the results from applying the modelling framework to the case study company. The paper finishes in section 6, with the conclusions and future research directions.

Theoretical background

In this section, features and implications of MTO/ETO production environments, focusing on the challenges in managing and monitoring these systems are explored. Then, works using simulation approaches, applied to MTO/ETO are revised and we delve on the role that hybrid simulation approaches may have in representing different processes in MTO/ETO production strategies. Finally, the capabilities, strengths and weaknesses of the three simulation methods– SD, DES, and ABS, are explored.

Implications on MTO/ETO combined production strategies

Even though MTO/ETO literature has received little attention, it is an important sector, with many small and medium enterprises operating under these strategies in different supply chains (Hendry 2010). These environments are characterized by different levels of customization, long flow times, variable demand, product specifications, lead times and process duration (Hicks and Braiden 2000).

MTO and ETO strategies differ in some respects. In MTO, the design of the product exists at the time of order entry, although some modifications may be considered (Hendry 2010), for a set of pre-defined parameters and attributes (Willner et al. 2014); only manufacturing and assembling the product occur after the order has been confirmed. In ETO, designing, manufacturing and assembling the products occur when the order has been confirmed (Hendry 2010), with the order lead time including the manufacturing, engineering design, and material acquisition. In ETO, product specifications are uncertain, with customers requiring the design of a completely new product (Akinc and Meredith 2015). The engineering process is simultaneously a bottleneck and a core process that is never outsourced (Grabenstetter and Usher 2015). Variability and uncertainty are critical in ETO environments, due the different projects simultaneously carried, with different completion levels, and constantly subject to changes (Adrodegari et al. 2015). The final products have complex structures that create many levels of assembly (Hicks and Braiden 2000), interfering in the production flow and coordination.

Most manufacturers do not exclusively manufacture under an ETO strategy, often earning most revenues from MTO products (Willner et al. 2014). In MTO and/or ETO environments, each product is tailored to the customers' needs. This translates into activities of design, production and delivery which are one of a kind, and can be modelled as the execution of a project. Low volume production is across MTO and ETO strategies. Different projects are simultaneously executed, competing for and sharing the same resources (Alfieri, Tolio, and Urgo 2012). Companies operating under these strategies are commonly organized as jobbing processes to achieve flexibility (Hendry 2010). Tardiness is an important measure of performance in MTO/ETO, because penalty costs depend on lateness, and early deliveries to customers may be an inconvenience. Other important measures of performance include resources' utilization and inventory levels (Hicks and Braiden 2000).

Simulation in combined production strategies

Different previous studies are concerned with simulation in combined production strategies. Wang et al. (2011) developed a simulation model for studying operational decisions in combined MTS/MTO production. The authors evaluated the effect of two operational decisions in the system performance, namely semi-finished modules inventory policy, and the order admission control. Findings showed that the reorder point and the maximum work-in-progress (WIP) level had interlinked impacts on throughput and lead time. An extension of the model was proposed in Wang et al. (2012), with the authors relaxing some of the assumptions made in the earlier version of the study. The authors quantified the impact on the system cost of the MTS production lead time and its variation and concluded that the MTS production lead time affected the system in the selection of the inventory policy and that a reduction in the MTS lead time could significantly reduce the total system cost. Also considering a combined MTS/MTO manufacturing system, Rocha et al. (2015) analysed the impact of two different mechanisms for releasing orders in the MTS and MTO stages. Results showed that reducing the percentage of tardy jobs could be achieved through a moderate increase in the level of stock of semi-finished products.

In Wu, Jiang, and Chang (2008), the authors explored the MTS/MTO strategy, in a semiconductor foundry. A scheduling method was proposed to achieve high levels of on-time delivery for MTO products and a high throughput for MTS products. Using DES, the authors assessed the performance of the proposed scheduling method and compared the results with other approaches in the literature. Beemsterboer et al. (2017) focused on four different methods for integrating MTS items in the control of a job-shop - MTO environment. The different methods were evaluated using DES in Python. A real factory working with mixed MTO, MTS and ATO strategies was considered in the study by Horng (2013). The author developed a simulation model for the combined manufacturing system, to assess different safety stock policies and performance.

Hicks and Braiden (2000) developed a simulation model based on the discrete event method, representing a MTO/ETO manufacturing facility operating under the control of a computer aided management system. The model represented the manufacture of different product families, using jobbing, batch, flow, and assembly processes. The authors collected several manufacturing performance measures and found that the performance of the different dispatching rules was different at the components and end items levels. At the component level, and for a job shop, the shortest operation time first rule led to the best results, while at the product level, the least slack first and the earliest due date first rules performed best. In a different approach, Zschorn, Müller, and Ivanov (2016) studied a manufacturing company focusing on hybrid MTO/ETO production at the tactical level capacity management. The authors used a linear programming approach for determining production capacity, considering a single work station case. Afterwards, the preliminary idea of an agent-based simulation for a multiple-line case analysis was presented.

The use of simulation in combined production strategies has mostly been focusing on MTS/MTO strategies, with fewer studies addressing the needs of combined MTO/ETO. The analysed literature does not focus on the activities of product development in ETO strategies, nor in the customization process in MTO strategies. Previous studies focused on production, for determining appropriate production scheduling and reorder points. We bridge this gap by establishing a conceptual model framework focusing on jointly analysing the development/customization and production tasks. This framework is useful for predicting the performance of the system under different demand patterns and operating policies. SD, DES and ABS methods are used for modelling and simulation of a MTO/ETO environment, and assessing performance in terms of tardiness, work-in-progress (WIP), and human resources utilization.

Potential of hybrid simulation approaches

Simulation allows studying the dynamic features of systems (Hicks and Braiden 2000), and is one of the most commonly used techniques in Operational Research (OR) (Swinerd and McNaught 2012). It is useful for modelling complex manufacturing systems, with applications including optimizing designs and operations, and assessing performance prior to implementation. Current demands from optimization, incorporation of human decision making, and high complexity of modern systems, push researchers for combining different simulation methods and achieving better understanding of complex interactions between processes of different nature (Swinerd and McNaught 2012). Developing a simulation model for a complex system using a single simulation method can be time consuming, and often the use of the methods may become inappropriate under certain circumstances. Considering the different nature of processes involved in MTO/ETO environments, a hybrid simulation approach becomes a valid alternative to study these systems.

Hybrid simulation approaches are becoming more relevant and frequent. However, combining two or more methods only is justified when the models from different methods are of equal importance for the overall goal of the simulation. This is due to the effort and precision required for combining models from different methods, and establishing information sharing. When the use of hybrid simulation is justified, many benefits are achieved. These include flexibility (Wang, Brême, and Moon 2014) and extraction of the best features of each simulation method, and the possibility of overcoming many challenges imposed by the complexity of modern systems (Swinerd and McNaught 2012). The purpose of hybrid simulation is solving complex real-world problems, using different methods to tackle different aspects of a given situation (Morgan, Howick, and Belton 2016), by complementarity of the strengths in each individual simulation method (Wang, Brême, and Moon 2014).

Examples of the use of hybrid simulation approaches include supply chain management (Umeda and Zhang 2008), enterprise simulation (Rabelo et al. 2005), hierarchical production planning (Venkateswaran and Son 2005), software project planning and management (Rus, Collofello, and Lakey 1999), material handling systems (Hao and Shen 2008), and life cycle assessment (Wang, Brême, and Moon 2014).

Simulation methods

Appropriate simulation model building starts with the adequate choice of method(s) for model development. Different simulation methods have different strengths and weaknesses, and understanding these is key for proper model development. The structure of the system and the objectives of the simulation should influence the choice of methods.

SD, initially called Industrial Dynamics, was proposed by Jay W. Forrester at the MIT, in the 1950s (Borshchev and Filippov 2004). It focuses on an aggregated view of the systems, and feedback mechanisms, with system changes associated to changes in the system structure. Its basic structures include sources, stocks, flows, sinks, feedback loops and variables. Finite differential equations capture interactions among sub-systems and feedback loops are responsible for dynamic complexity (Lättilä, Hilletofth, and Lin 2010). Its common applications include strategic planning, supply chain, workforce management, software development, markets and competition, manpower and personnel, and project management (Lättilä, Hilletofth, and Lin 2010; Borshchev and Filippov 2004). It is a continuous simulation method, in which neither mapping discrete events is possible, nor considering detailed information.

Unlike SD, DES, whose origins date back to the 1960s, requires using accurate data about the system's operation. Its most important elements include entities, activities, resources, queues, and events, with entities acting as passive elements flowing through blocks of activities, queues, suffering delays, seizing and releasing resources (Borshchev and Filippov 2004). The model state variables change in discrete points in time – events. DES has commonly ben applied to manufacturing settings, for evaluating alternative routing, planning and scheduling (Rabelo et al. 2005), warehouse operations, pedestrian movement, and traffic models. High data demands are one of the flaws of DES.

ABS adopts a microscopic approach, with agents exhibiting behaviour at the individual level; the macro-level behaviour results from the individual agents' interactions (Wang, Zheng, and Zhao 2013). Agents in an environment communicate with each other according to pre-defined rules and may present properties as proactiveness, reactiveness, responsiveness, social and leaning ability, learning, and spatial awareness; may be representative of entities in a system, as human beings, animals, or institutions rules (Borshchev and Filippov 2004). ABS has been used in applications in businesses, including manufacturing, supply chain management, maintenance (Lättilä, Hilletofth, and Lin 2010), and individual behaviour rules (Borshchev and Filippov 2004). As many details as possible are used for representing the characteristics of the elements in the system, and there is a high data demand, which may be challenging.

Borshchev and Filippov (2004) reported several application areas for the simulation methods. Considering the applications reported and the scope of this work, we are interested in the applications of manpower and personnel, project management, and factory floor. Manpower and personnel is important due to the many human resources in MTO/ETO environments, both in production and project development. It is usually modelled using SD and ABS, whereas SD focuses on workforce management issues (Aburawi and Hafeez 2009), and ABS on the individual agents' behaviour (Borshchev and Filippov 2004). The new product development in ETO can be modelled as a project, which justifies the need to consider project management in the model, commonly simulated using SD. Finally, shop floor operations, are modelled using DES, which is the simulation method we adopted for the production stage.

Considering the above, we propose using a novel hybrid simulation approach (Barbosa and Azevedo 2015) to analyse the complex MTO/ETO manufacturing environment.

Conceptual framework

Conceptual modelling corresponds to abstracting a model from a real system. Considering the objectives of the simulation, the modelling stage is important for defining the key features of the system, the methods to use in developing the simulation model, the data requirements, the validity of the model and the level of confidence given to the model results (Robinson 2008).

Our research objective is developing a model for performance assessment of a MTO/ETO combined manufacturing environment operating under different policies, considering the relevant competitive dimensions and main system features. In the first stage of problem analysis, the hybrid simulation model is constructed, considering the specific features of combined MTO/ETO environments. Building on the identified applications for the different simulation methods, the system structure and most suitable simulation methods for analysing each part of the MTO/ETO environment are discussed and assessed.

To assess the model results for the system operating under different policies, and understanding the differences in the performance measures, appropriate statistical techniques are required. Selected statistical techniques must allow comparing alternative scenarios and searching for a solution to the problem being analysed (Robinson 2004). A one-way analysis of variance (ANOVA), followed by a Tukey-Kramer's post hoc comparison allows assessing the statistically significant differences in performance for the different operating policies. Finally, factorial design from DOE methodology (Antony 2014) is used for generating and assessing the effect of different system parameters in the relevant performance measures.

Hybrid simulation model

Conceptual model building started with identifying the relevant system features, the simulation methods to use in the different system parts and the information sharing between modules from different methods. Figure 1 presents an overview of the use of the simulation methods and the target system parts. SD was used at a higher abstraction level, modelling the project management tasks in ETO and the customization tasks in MTO. Each new project for developing products under the ETO strategy was considered an agent, with a built-in SD behaviour. The SD method was also used for modelling the function of hiring staff for the development of projects, considering the projects' needs. Each project developer, henceforth called developer, was modelled as an agent, whose internal state influenced the number of developers available for project development and customization. The SD model of hiring developers influenced the number of active developers and the developers' internal state influenced the allocation to the project development. When the development of a project or customization tasks finished, production started. The shop floor operations were modelled and simulated using DES, with the shop floor employees and machine resources modelled as entities. In the proposed model, despite the model being built in a main agent, there is no direct interaction between DES and ABS models.

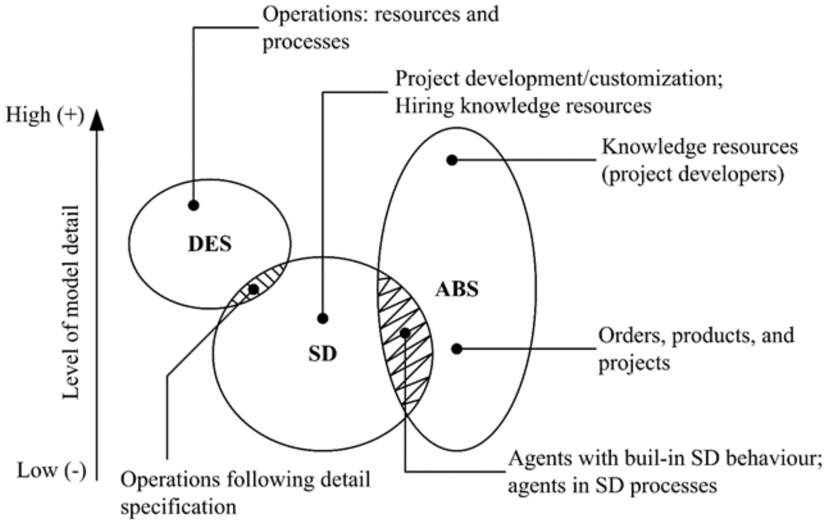


Figure 1. Modelling hybrid simulation approach and MTO/ETO manufacturing system parts.

Figure 2 presents the detailed model architecture, built upon the specifications set in Figure 1. There are six modules in the system, namely, the order prioritization, order specification detail - customization, new product development -, workforce allocation, workforce management, production - production normal, production special -, and developers. Each module is explained in detail in the following sections. Orders may be for standard products – MTO oriented orders -, or may be for special projects – ETO oriented orders.

Different model designs can be adopted in hybrid simulation approaches (Barbosa and Azevedo 2017; Morgan, Howick, and Belton 2016; Swinerd and McNaught 2012). The model runs in a generally integrated design, with simultaneous modules' execution and feedback mechanisms between the different modules. The order prioritization model is executed once in the beginning of each week of simulation to assess the new orders. Then, the order specification detail modules follow, according to the type of order (ETO or MTO). The order specification modules for ETO and MTO oriented orders do not interact, but share common resources, the developers. The order specification detail and production modules occur sequentially, with production following customization and new product development. The workforce allocation function is executed upon call, in discrete points in time, establishing bi-directional communication with the developers and order specification detail modules, as represented in Figure 2.

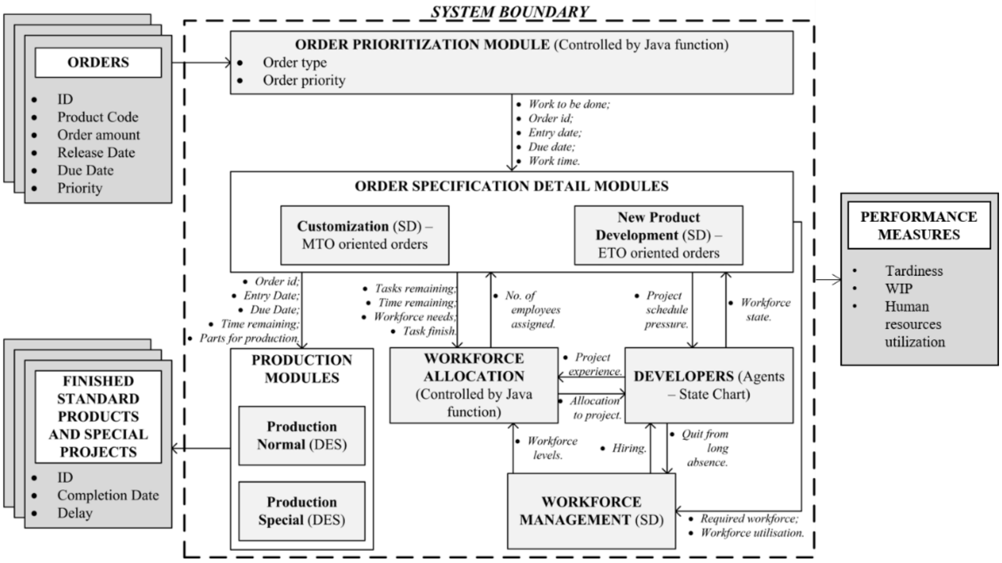


Figure 2. Detailed architecture of the hybrid integrated SD-DES-ABS model for performance assessment in manufacturing environments with combined MTO/ETO production strategies.

In the modelling framework, multiple orders for standard products and new product development projects are allowed. The model assumes prior approval of the orders input to the system. The deliveries of finished products/projects, are not in the scope of the model. Once an order is completed, it is removed from the system, with a record of its delay.

Order prioritization

In the beginning of each simulation week, new orders are input to the system, by the execution of an event called *Demand*. In the order prioritization module, orders are sorted by the due date and a priority level. First, the system verifies the order type – standard products or special projects. When the order is for standard products, the system verifies the due date of the new order and compares it with the orders in the system. When the due date of the new order is before the due date of the orders in the system, the new order is given priority over the existing ones – earliest due date first (EDF). If the due date of the new order is later than the existing orders, the new order is placed in last position. In case of due date equality with the existing orders, the orders' priorities are compared. If the priority of the new order is higher, the new order is given priority, otherwise is placed as the least prior among those with equal due date.

When the new order is for an ETO product, henceforth called special project, the project due date is considered. A percentage of the total time available for the special project is allocated to the development stage, and the remaining is allocated to production. The special project is input to the system and the resources are allocated to it in the resource allocation module. The special project development starts immediately.

Order specification detail

After orders' sorting, these are allocated to customization or special projects categories. The order specification detail modules correspond to the customization (MTO) and special projects' development (ETO). ETO products own the features of a project: temporariness and uniqueness, hence, every product is the result of a project (Yang 2013).

Despite the relevance of traditional project management tools, as the programme evaluation and review technique (PERT) (Sterman 1992), which consider a sequential and functional approach during development (Rodrigues, Dharmaraj, and Rao 2006), these do not address the dynamic complexity created by delays, interdependencies, and multiple activities that exist in large projects (Sterman 1992). SD models are good at capturing the dynamic behaviour of factors associated to projects and interactions among them. These have been widely and successfully used in managing development projects, where managing the project takes a holistic view of the system, focusing on feedback mechanisms, allowing understanding the connection amid project dynamics and performance (Rodrigues 1994). The project development is modelled considering an initial stock of work to be done and a final stock of finished work. The finished work flows from work to be done to finished work, considering the staff allocated to the project, but ignoring which work is done and by whom it is done. Disruptive factors in project execution may be considered, as rework, change in project scope, quality compliance, and productivity (Rodrigues 1994).

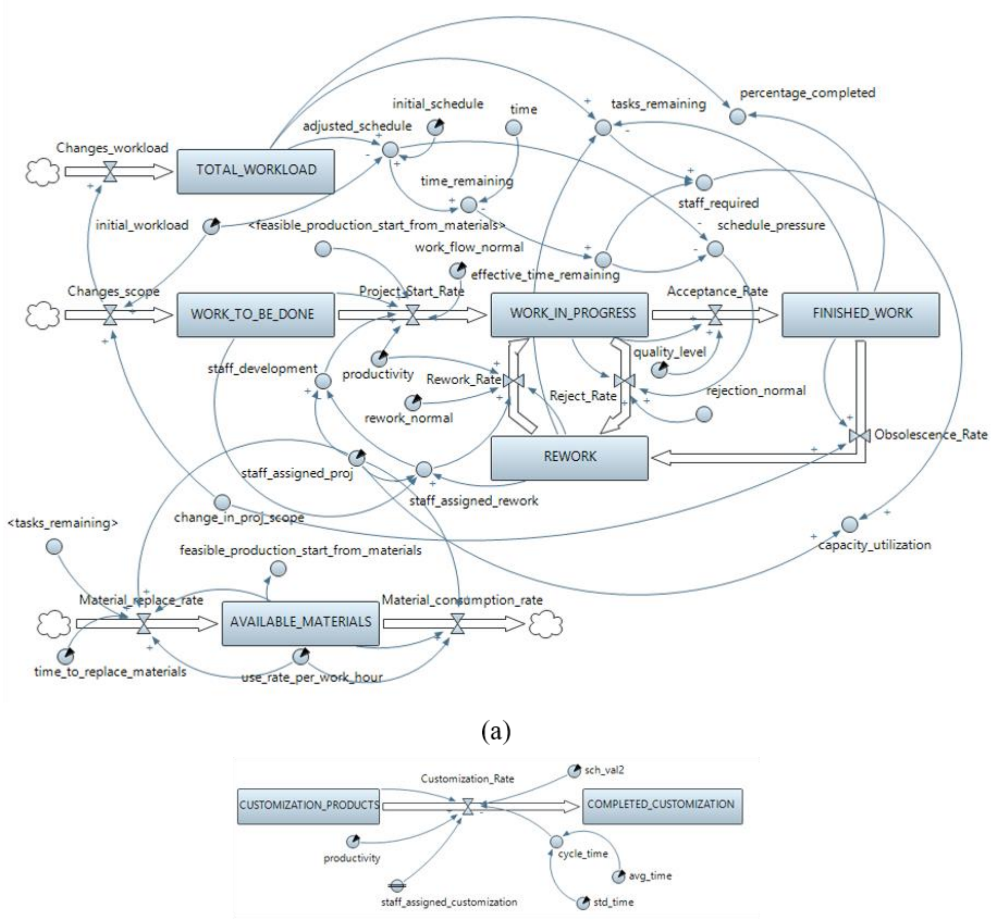
To address the effects of dynamic changes during project development, we used SD for the project development and customization. Different computer models using SD for project management have been reported in the literature. Huot and Sylvestre (1985) developed a SD model for the construction management of a major building. The model consisted of three subsystems, including design, construction and procurement progress. Sterman (1992) described the use of SD for the management of large scale projects, and discussed the appropriateness of the method as an analytical tool in the NPD process. Also, Rodrigues and Bowers (1996) discussed the role of SD approaches in project management. Lyneis and Ford (2007) described the core model structure groups used in SD models in NPD, including project features as a collection of tasks performed in sequence or in parallel, the rework cycle, that represents a major source of challenges, the project control, intended for modelling the efforts in closing a performance gap, and the ripple and knock-on effects, that represent the impact that project control efforts have on rework and productivity. Rodrigues, Dharmaraj, and Rao (2006) developed a SD model to analyse the product development dynamics and assess the competence loss of project staff when project scope changes occur. This model is a refined version of the model by Balaji and James (2005), by considering the competence loss. The SD model by Reddi and Moon (2013) addresses the interactions between the NPD and the engineering change management processes at the supply chain level. Different supply chain actors interact with the original equipment manufacturer (OEM) in different stages of the NPD process. Despite the relevance of this model, it is designed to be applied at the supply chain level and considering multiple actors involved in the NPD process. Also, DES could be a useful method for modelling the NPD process, especially for considering engineering changes, however, this would result in complex and large amounts of data (Reddi and Moon 2013). Given the successful application of SD to NPD, and as we are considering a more firm-centric NPD process, we adopted the model by Rodrigues, Dharmaraj, and Rao (2006) for developing and managing special projects.

To tackle constraints from material resources, missing in the original model by Rodrigues, Dharmaraj, and Rao (2006), we added a stock of materials, Figure 3(a), affecting the project development. Each project is an agent, whose internal behaviour is represented in SD. Customization tasks are a simplified representation, with an initial stock of orders for customization, and orders flowing from customization products to completed customization depending on the staff allocated to customization, as in Figure 3(b). Low variability in the "*cycle_time*" was considered for customization, as these are routine tasks.

The order specification detail modules receive information from the order prioritization module. For standard products, the customization module receives the number of orders to be customized. To calculate the developers allocated to customization, a time frame is established for completing these tasks. The special projects receive information about workload, the project due date and the project entry date. In the simulation, there is a schedule determining the working hours. An event, *Schedule Eval*, assesses the state of the schedule. When the schedule is off the parameter *"sch_val2"* (Figure 3(b)) is set to zero by the event, and the rate of the tasks is set to zero; when the schedule is on, this parameter is set to one. The schedule value influences all activities in the system.

The workforce levels in each special project and customization tasks are dynamic, and given by the parameters *"staff_assigned_proj"* and *"staff_assigned_customization"*, in Figure 3. Whenever a developer is missing from work or providing support to other developers, its contribution to the project or customization is not considered. The *"productivity"* in each project depends on the developers allocated to the project, and is given by equation 1:

$$productivity_i = \frac{prod\ exp\ dev \times no.\ exp\ dev_i + prod\ new\ dev \times no.\ new\ dev_i}{total\ number\ dev_i}, (1)$$



(a)

(b)

Figure 3. Implementation modules. (a) Special project development module; (b) Customization tasks.

where *productivity*$_i$, *no. exp dev*$_i$, *no. new dev*$_i$, and *total number dev*$_i$ are, respectively, the productivity factor, the number of experienced developers, the number of new developers, and the total number of developers in project *i*; *prod exp dev* and *prod new dev* correspond to the productivity factors associated to experienced and new developers.

During project development, there is a constant update of the required workforce and the workforce capacity utilization. These are given by equations 2 and 3, respectively:

$$staff\_required_i = \begin{cases} tasks\_remaining_i / effective\_time\_remaining_i \,, & effective\_time\_remaining_i > 0 \\ maximum\ admissible\ workforce \,, & otherwise \end{cases}, \qquad (2)$$

$$capacity\_utilization_i = \frac{staff\_required_i}{staff\_assigned\_proj_i}, \qquad (3)$$

where *staff_required*$_i$, *tasks_remaining*$_i$, *effective_time_remaining*$_i$, and *staff_assigned_proj*$_i$ correspond, respectively, to the developers required to accomplish the delivery date, the tasks which have yet to be fulfilled, the time remaining until the end of the project, excluding weekend and schedule off hours, and the number of staff allocated to project *i* by the workforce allocation function. The required staff when the project exceeds the due date is set to a maximum admissible number of developers.

Production

Production of the standard products and the special projects starts after the order specification detail activities. DES, as referred in section 2.4. is widely used at the operational level, allowing studying processes as sequences of activities, with entities flowing through those activities. It allows tracking the status of individual entities and resources in the shop floor, for estimating performance measures associated with those entities (Venkateswaran and Son 2005). For this, DES was selected for representing shop floor operations.

An event is triggered when customization and/or special projects development finish, and production starts. The production module requires the type of product and the amount to be produced as input, and the parameters for the processing times stochastic distributions. Even though the orders are input for production according to their due date, different queueing rules (EDF, first-in-first-out (FIFO), priority based, and shortest processing time first (SPTF)) are used for the products flowing through the production system. When the number of components in an order is produced, the order is considered finished. For shop floor resources allocation, special projects are always given priority over the standard products.

Workforce allocation

In the literature referring to multi-project management, the resource allocation between simultaneous projects is a main topic (Engwall and Jerbrant 2003). For this, the workforce allocation function is relevant in the context of this work.

The workforce allocation function was developed in Java code. First, the proportion of staff to be allocated to each project is calculated, based on the workforce needs of each project – given by the parameter *"staff_required"*, Figure 3(a), from the special projects - and that the customization tasks must be completed within an established time frame, as represented in equations 4 and 5:

$$proportion\ staff_i = \frac{staff\ required_i}{\sum_i staff\ required + staff\ required\ customization}, \quad (4)$$

$$staff\ required\ customization = \frac{tasks\ in\ customization}{time\ frame\ (in\ hours)}, \quad (5)$$

where *proportion staff*$_i$ is the proportion of staff to be allocated to project *i*, *staff required customization* is the total staff that should be allocated to customization, and *tasks in customization* is the total number of standard products that must be customized.

Following, the *proportion staff*$_i$ is multiplied by the number of developers available, to assess the number of developers to assign to each project. For the time zero of simulation, the developers are randomly assigned to the projects, respecting the calculated values of staff to be assigned to each project and to the customization tasks. For the remaining re-evaluations of the workforce allocation function, the project developers are preferentially attributed to the project in which they spent most time. In case the preferred project already has all the developers assigned, the developer is assigned to another random project which not yet has all developers assigned.

The workforce allocation function is called upon the following situations: beginning of the simulation, beginning of every week, when executing the event *Demand*, for re-assessing the workforce needs of each project, and updating the developers' population when a new developer has been hired; when a developer quits from job; when customization tasks end; and when a special project ends.

Workforce management

Workforce management refers to assessing the current workforce, determining future needs and finding the gap between these for establishing solutions that aid in accomplishing the organizational needs (Lianjun et al. 2007). It is key for ensuring the availability of adequate workforce in the appropriate time and place (Aburawi and Hafeez 2009). Workforce management deals with subjective yet quantifiable variables as workforce skills and ability. It includes activities as recruiting, selecting, classifying, training, performance management and retention (Lianjun et al. 2007).

SD is widely used in assessing the dynamics of human resource management. Considering the work in Lianjun et al. (2007), we developed a simplified SD workforce management model for the project developers, considering the hiring and selection processes, and excluding the training, performance management and retention functions. The model has three stocks, *"Hiring in Process"*, *"Total Developers"* and *"Expected Utilization"*. The *"Total Developers"* stock represents the current number of developers, *"Hiring in Process"* the number of people being considered for hiring, and *"Expected Utilization"* the forecasted levels of the developers' utilization, based on the values recorded in the order specification detail modules. Without projects in the system there is no hiring of developers. Hiring depends on the gap between the current number of developers and the difference between the required and the desired workforce, considering the projects' needs calculated in the order specification detail modules.

A maximum allowable workforce is imposed to the model, to avoid sudden hiring near the end of the projects or when projects are delayed. All candidates who are hired start as unexperienced developers. Progression to experienced developers is achieved in the project developers' module.

Project developers

In the overall system, each developer is an agent, with a defined internal state. The effort of developers may vary over time, considering their availability or joint execution of different activities (Alfieri, Tolio, and Urgo 2012); thereby we consider the developers state one of the most important drivers of project execution and success.

Each developer is an agent, whose initial state is defined as experienced or new employee. New and experienced developers may be absent or working; yet, while the working stare of new developers is simple, for experienced developers it is sub-divided as on job or training, as in Figure 4. The following assumptions are valid:

- Training function occurs when there are new developers;
- New developers are more likely to be absent than experienced developers;
- New developers become experienced according to a training rate;
- Developers can quit from job;
- The probability of a developers becoming absent increases when there are no special projects in the system or when the pressure in the project the agent is allocated to is higher than a given value;
- Developers statistics, as time active, time absent, time allocated to each project, time training may be retrieved, and projects assigned to may be recorded by the action of an agent internal event called Time in Project.

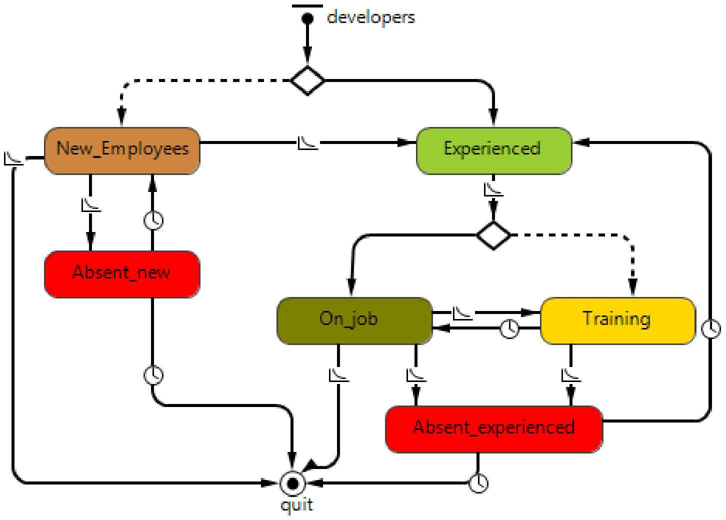


Figure 4. A state chart of the project developers.

Communication between modules

The proposed approach requires communication between models from different methods. The communication between these must occur timely, and with the appropriate information. Following, we describe the modules' communication.

Order prioritization – Order specification detail. The order prioritization module has impact in the order specification detail modules; the opposite does not occur. The event *Demand*, inputs the orders in the combined MTO/ETO system. When it occurs, the week orders are sorted in the order prioritization system and for each order, an agent is created.

Each special project is an agent in the order specification detail; for standard products, new orders are placed in a stock of orders to be customized.

Order specification detail – Production. An event, *Add Production*, is triggered when the stock of customized products increases one unit. This causes a standard order release to the shop floor and the event restart. For special projects, when the finished work equals the total project workload, the project development finishes and the project is input for production.

Order specification detail – Workforce allocation. When the workforce allocation function is called, the order specification detail modules transmit information to the workforce allocation function, concerning tasks remaining, required workforce, time remaining for the special project, and, when applicable, the project finish. In the opposite direction, the workforce allocation establishes the number and id of the developers to be allocated to the projects.

Order specification detail – Developers. When a developer is assigned to a project and is absent or training new developers, this is reflected in the staff allocated to the projects. Every minute of simulation, the state of the developers and the number of real project developers contributing to the project are updated, through an event called *Evaluate Staff State*. An absent or training developer is assigned to a project, but is not contributing to the development in a certain period, affecting the productivity factor in the project.

Each project is associated to a schedule pressure. When the schedule pressure exceeds a certain value, it increases the rate of the developers becoming absent from work.

Order specification detail – Workforce management. The order specification detail modules provide information to the workforce management module. The event *Evaluate Staff State* assesses the workforce required for each project and the workforce utilization, and inputs the values to the workforce management.

Workforce allocation – Developers. The workforce allocation function establishes the developers assigned to each project. A re-evaluation occurs when the workforce allocation function is called. Each developer has a record of the time spent in each project, information used by the workforce allocation function. Each developer will preferentially be assigned to the project he has spent more time in.

Workforce allocation – Workforce management. The workforce allocation function must know the levels of project developers. When it is called, the level of staff in the workforce management module is input to it.

Workforce management – Developers. Through the *Demand* event, the workforce levels in the workforce management module are verified. A new developer is created when hiring occurs. When a developer quits, the developers' stock is immediately reduced one unit.

Assessment of significant differences among operating policies

The second stage of the problem analysis encompasses assessing the significant differences among performance levels obtained for different system operating policies. This includes comparing alternative scenarios and developing a better understanding of the system. The analysis of variance (ANOVA) is a rigorous mean for assessing if changes in experimental factors have an effect in the system response and has been used along with simulation experiments (Robinson 2004) for comparing alternative scenarios. Given the objective of assessing differences in the system in response to alternative operating policies, a one-way ANOVA analysis followed by a post hoc Tukey-Kramer's test are considered appropriate for the analysis of the results.

Statistical analysis of variance (ANOVA) is often used along with simulation tools for interpreting data and assessing differences among the average performance of groups of items (Marzouk, ElMaraghy, and ElMaraghy 2016). The ANOVA test of hypothesis shows an overall difference between group means, and considers the comparison of two independent estimates of the variance of the population. The one-way ANOVA test does not allow inferring which groups of items differ, requiring post hoc comparison procedures for testing the differences among group means. Post hoc tests, as the Tukey-Kramer's, are used after the ANOVA test. The Tukey-Kramer's test can control type 1 errors (Ostertagová and Ostertag 2013), and was selected for the post hoc comparisons.

Assessment of relevant system parameters impact in performance

The final stage of the problem analysis encompasses determining the system parameters, related to human resources and the project development, which influence the performance of the system. To conduct the analysis we used full factorial design methodology of DOE (Antony 2014) to create the simulation input parameters and assess the model results. Experimental design is primarily used for identifying important experimental factors that give most improvement in meeting the purposes of the simulation study (Robinson 2004).

Designed experiments are used for intentionally making changes to input system factors, and observing the changes in the process output. The information obtained can be used for improving the systems' performance. DOE encompasses planning, designing and analysing an experiment, so proper and valid conclusions may be retrieved.

Building on the previous discussion, Figure 5 shows the resulting proposed conceptual framework, including the hybrid simulation model development and the model application and results' analysis. An overview of the conceptual model steps is provided in the flow chart in Figure 6.

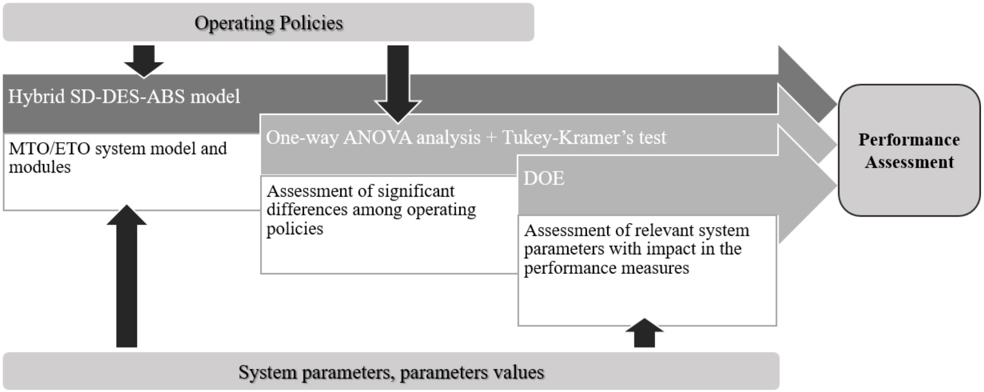


Figure 5. Proposed framework for the hybrid simulation model in MTO/ETO environments, with the model application and assessment of model output.

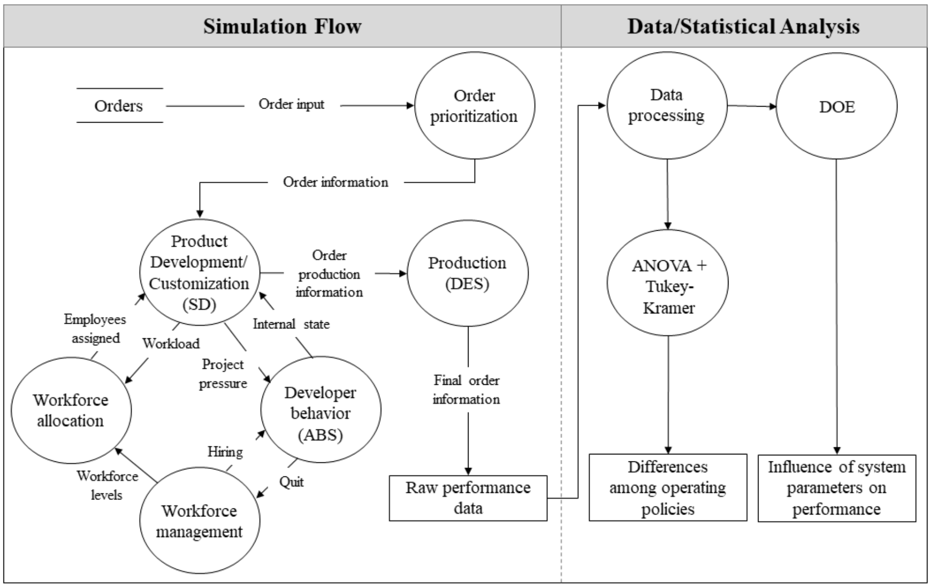


Figure 6. Conceptual model flow diagram.

Application case

The case study company

To apply and test the proposed framework, the case of an advanced manufacturing company, producing customized high -technological conveyors, packaging and robotised palletisers solutions for the food and chemical industries, has been considered. The company operates in a combined MTO/ETO strategy, in a single facility, working in a process layout, with general-purpose equipment, low volume operations, and high mix of products. Machines are grouped by function, and buffers guarantee material flows between machines. A total of six Work-Centres (WCs) make the production and assembly areas. Each WC has different number of machines – two in WC1, four in WC2, one in WC3, one in WC4, three in WC5 and two in WC6. The company produces standard products in a MTO strategy that prior to production are customized. Each standard product type follows a different route in the shop floor and has different processing times in each WC. Seven standard product families have been considered for the simulations, with the routes and processing times as in Table 3 from Appendix 1. Quality inspection occurs after each operation, in each WC, and requires in average two minutes. The facility works from Monday to Friday, from 7a.m-12p.m. and 1p.m.-7p.m.

The special projects are unique products that undergo an engineering process, including product specification, design, and selection of materials. Special projects' development encompasses interaction with the customer, and the product requirements are often changed. A specialized team develops the products to the customer's requirements and customizes the products in the company portfolio. The special projects and the standard products, compete for resources at the production and development/customization levels. Table 4 in Appendix 1 shows the average and standard deviation production times, in days, for the special projects in each WC. The values in Table 4 are estimates, as each special project is unique and processing times are highly variable. The special projects undergo processing in all WCs, but in WCs 3 and 4, where one machine is available, alternative machine resources are used. All processing times followed a normal distribution.

The selection of the case study company considered that this industrial setting is a good representative of the features of MTO/ETO combined environments. The case company operates with different levels of product customization. As above referred, the company performs some parts customization in standard products and develops new, fully customized products through special projects. Also, it operates with long flow times, that can vary from a couple of weeks to a few months, under highly a highly variable demand pattern, with often uncertain product features, lead times and processes duration. It operates in a jobbing process, and internally develops activities of design, production and delivery.

Implementation, validation, and testing

The model was implemented using the Anylogic platform. The choice of the software considered the multi-method modelling possibility, which enabled building the models combining SD, DES and ABS. Anylogic is a software based on Java that allows combining the three modelling methods in the development of a single model.

Model validation and verification are critical to ensure the model provides accurate information about the system under study. A model should be valid for the purposes it has been developed for. For verification purposes, the model was subject to intensive debugging by multiple runs and individual verification of each module's output, using different problem instances. As for validation purposes, and following some of the techniques proposed in (Sargent 2011), the model was subject to extreme condition tests, internal validity, operational graphics, and parameter variability.

Results and analysis

The model has been simulated to assess the effect of different demand data and process parameters on selected performance measures – tardiness at the product level, WIP, measured as the number of components in the system or the number of projects in production, human resources utilization, and late deliveries count. It considered the time units in hours and a fixed time step of 1x10-5. The integration type was Euler and the model simulated six months of operations. The results presented are the average values from multiple simulation runs. In the first stage of problem analysis, the demand data was varied and the different operating policies considered were queuing policies:

- EDF – orders with lower due dates are given priority;
- FIFO – ordering per arrival;

- SPTF – orders with shortest processing times are given priority;
- Priority based – EDF (PB-EDF) –orders with lower due dates and higher priority are given priority;

Secondly, considering a fixed demand pattern and operating policy, the impact of four process factors was considered at two levels – low and high.

Variable demand data and queuing policies – one-way ANOVA analysis and Tukey-Kramer's test

The first stage of the model output assessment considered different demand patterns and queuing policies. The demand patterns included no orders for special projects (No SP), 10% of orders for special projects (10% SP), and 20% of orders are for special projects (20% SP). The parameters' values in Table 5 in Appendix 1 were kept constant throughout the experiments. Minitab was used for data analysis.

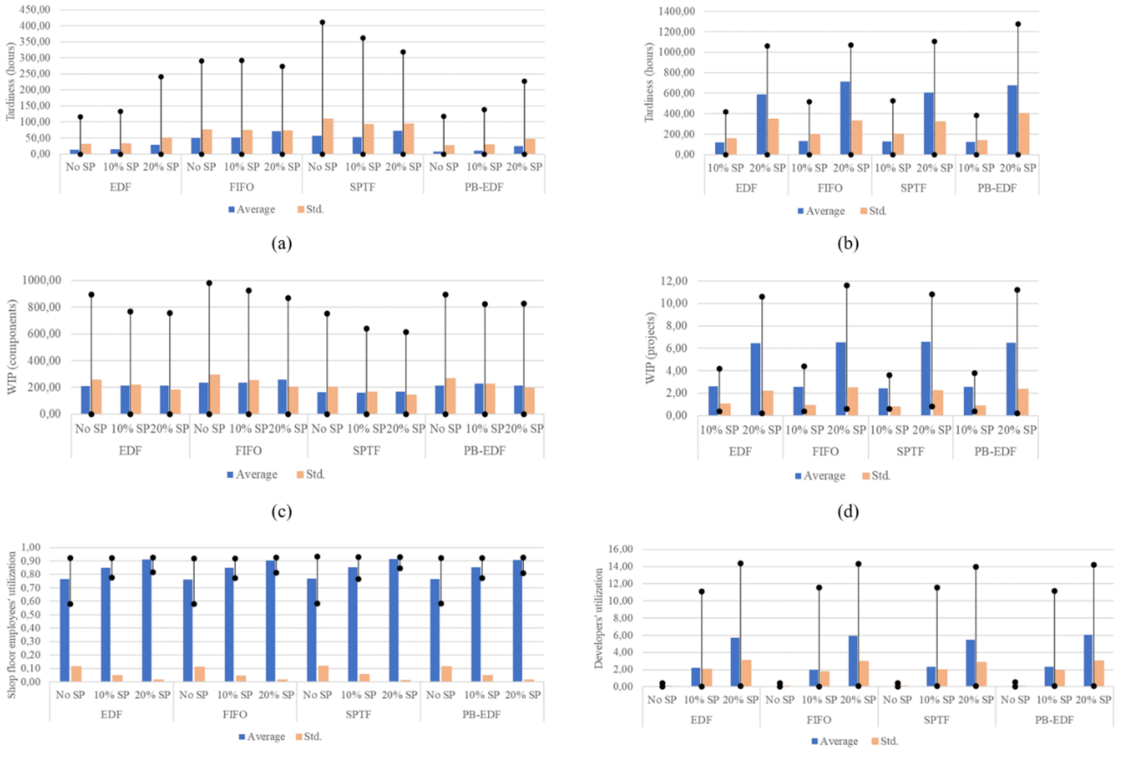
Figure 7 presents the average, standard deviation, maximum and minimum values for the different performance measures. The SPTF policy, Figure 7(a), achieves the highest average and maximum tardiness values for standard products, performing worst among the queuing policies. The EDF and PB-EDF policies achieved the lower tardiness values for standard products. Despite the increase in the tardiness of the special projects when the demand rises from 10% to 20%, Figure 7(b), the recorded tardiness for the special projects is similar among the different queuing policies. The one-way ANOVA analysis, with alpha=0.05, Table 1(a), shows significant differences in the tardiness of standard products for different queuing policies, but no significant differences in tardiness for the special projects in the same demand pattern, among different queuing policies. The Tukey-Kramer test, Table 1(b) shows that for different demand patterns, in the standard products, the EDF and PB-EDF, and the SPTF and the FIFO policies perform similarly.

The tardiness measures, for MTO products, at the product level, show that queuing policies considering the due date information of the product outperform policies based on the order of arrival and the processing time. This agrees with previous findings (Hicks and Braiden 2000; Lu, Huang, and Yang 2011) showing that, at the product level, EDF rules achieve better performance, while SPTF achieve worst performance levels. The absence of differences in performance for the different queueing policies for ETO products, may be explained by the fact that ETO projects were always given priority over the MTO products. For this, the problem of deciding the queue position of the ETO components was not applicable.

The WIP levels, measured as the number of components in production, for the standard products are presented in Figure 7(c). For the special projects, Figure 7(d) presents the results for the number of special projects in production. The ANOVA results in Table 1(a) show significant differences in the WIP levels for the different queuing policies, in the different demand patterns, except for the WIP of the special projects when 20% of orders are special projects. Differences in the WIP performance for higher percentage of special projects are negligible. The Tukey-Kramer's test results show the SPTF policy performing best for the WIP of the standard products, with the lowest WIP values. The achieved performance levels for the SPTF policy may be justified by the fact that under this policy, jobs tend to wait less time to be processed (Eilon and Cotterjll 1968). Considering this, queues at the work centres and the WIP levels, measured as the number of components in production, tend to be smaller.

The shop floor employees and developers' utilization levels are presented, respectively, in Figure 7(e) and Figure 7(f). Increases in the demand for special projects increases the average resources' utilization. According to the results in Table 1(a), when there are no orders for special projects, neither the shop floor employees' utilization, nor the project developers' utilization vary significantly. This is in agreement with the literature (Eilon and Cotterjll 1968), where the resources idle time is independent of the queuing rules, but dependent on the workload. An increase in the demand for special projects induces significant differences in the human resources utilization values, as the one-way ANOVA and Tukey-Kramer test show. Despite achieving significantly different results, it is not possible assessing a single best queuing policy for the human resources utilization.

In Figure 7(f), the developers’ utilization exceeds the unit, meaning lack of resources to complete all the planned projects on schedule. To accomplish responsiveness, the utilization should be below the unit (Ulrich and Eppinger 2012).



(a) (b)

(c) (d)

(e) (f)

Figure 7. Average, standard deviation, maximum, and minimum values for: (a) Tardiness standard products. (b)Tardiness special projects. (c) WIP standard products. (d) WIP special projects. (e) Shop floor employees’ utilization. (f) Developers’ utilization.

Table 1. Comparison of the different queuing policies under different demand patterns for the different performance measures. (a) one-way ANOVA. (b) Tukey-Kramer’s test.

(a)			**Degrees of freedom**	**Sum of squares**	**Mean square**	**F-value**	**P-value**
No SP	**Tardiness standard products**	**Between groups**	3,00	160952,00	53651,00	11,22	0,00
		Within groups	340,00	1626448,00	4784,00		
		Total	343,00	1787400,00			
	WIP standard products	**Between groups**	3,00	5849856,00	1949952,00	30,14	0,00
		Within groups	8632,00	558516155,00	64703,00		
		Total	8635,00	564366011,00			
	Shop floor employees’ utilization	**Between groups**	3,00	0,08	0,03	2,18	0,09
		Within groups	17268,00	220,83	0,13		
		Total	17271,00	220,91			
	Developers’ utilization	**Between groups**	3,00	0,01	0,00	1,04	0,37
		Within groups	8732,00	32,32	0,00		
		Total	8735,00	32,33			
10% SP	**Tardiness standard products**	**Between groups**	3,00	138096,00	46032,00	11,64	0,00
		Within groups	340,00	1344134,00	3953,00		
		Total	343,00	1482230,00			
	Tardiness special projects	**Between groups**	3,00	838,00	279,40	0,01	1,00
		Within groups	22,00	652623,00	29664,70		
		Total	25,00	653462,00			
	WIP standard products	**Between groups**	3,00	7192498,00	2397499,00	50,97	0,00
		Within groups	8632,00	406064934,00	47042,00		
		Total	8635,00	413257432,00			
	WIP special projects	**Between groups**	3,00	37,77	12,59	15,32	0,00
		Within groups	8872,00	7292,67	0,82		

		Total	8875,00	7330,44			
	Shop floor employees' utilization	**Between groups**	3,00	0,08	0,03	10,90	0,00
		Within groups	17268,00	40,52	0,00		
		Total	17271,00	40,59			
	Developers' utilization	**Between groups**	3,00	131,90	43,96	11,79	0,00
		Within groups	8732,00	32563,10	3,73		
		Total	8735,00	32695,00			
20% SP	**Tardiness standard products**	**Between groups**	3,00	174306,00	58102,00	12,38	0,00
		Within groups	340,00	1595901,00	4694,00		
		Total	343,00	1770207,00			
	Tardiness special projects	**Between groups**	3,00	117504,00	39168,00	0,32	0,81
		Within groups	43,00	5300221,00	123261,00		
		Total	46,00	5417725,00			
	WIP standard products	**Between groups**	3,00	8628932,00	2876311,00	88,63	0,00
		Within groups	8632,00	281082615,00	32563,00		
		Total	8635,00	289711547,00			
	WIP special projects	**Between groups**	3,00	22,90	7,64	1,44	0,23
		Within groups	9232,00	49075,80	5,32		
		Total	9235,00	49098,70			
	Shop floor employees' utilization	**Between groups**	3,00	0,20	0,07	444,89	0,00
		Within groups	17268,00	2,57	0,00		
		Total	17271,00	2,76			
	Developers' utilization	**Between groups**	3,00	435,80	145,25	16,25	0,00
		Within groups	8732,00	75118,40	8,60	8,60	
		Total	8735,00	75554,10			

(b) SD – Significantly different; NSD – Not significantly different

Comparison	**Tardiness standard products**			**WIP standard products**			**WIP special projects**	**Shop floor employees' utilization**		**Developers' utilization**	
	No SP	**10% SP**	**20%SP**	**No SP**	**10%SP**	**20%SP**	**10%SP**	**10%SP**	**20%SP**	**10%SP**	**20%SP**
EDF - FIFO	*SD*	*SD*	*SD*	*SD*	*SD*	*SD*	*SD*	*NSD*	*SD*	*SD*	*NSD*
EDF -. SPTF	*SD*	*SD*	*SD*	*SD*	*SD*	*SD*	*SD*	*SD*	*SD*	*NSD*	*NSD*
EDF - PB-EDF	*NSD*	*NSD*	*NSD*	*NSD*	*NSD*	*NSD*	*NSD*	*SD*	*SD*	*NSD*	*SD*
FIFO -. SPTF	*NSD*	*NSD*	*NSD*	*SD*	*SD*	*SD*	*SD*	*SD*	*SD*	*SD*	*SD*
FIFO - PB-EDF	*SD*	*SD*	*SD*	*SD*	*NSD*	*SD*	*NSD*	*SD*	*SD*	*SD*	*NSD*
SPTF -. PB-EDF	*SD*	*SD*	*SD*	*SD*	*SD*	*SD*	*SD*	*NSD*	*SD*	*NSD*	*SD*

The late deliveries count considered the percentage of delivered orders against the total orders for the simulated period, and the percentage of orders delivered, delayed. Table 2 shows that in the simulation period, all demand for standard products is fulfilled in the different queuing policies, however, a higher percentage of the delayed deliveries is generally verified for the FIFO policy, and lower percentage for the PB-EDF policy. This agrees with the literature (Mizrak and Bayhan 2006), that identified the EDF policy as one of the best performing in terms of the proportion of tardy jobs achieved in a job shop environment. When 10% of the orders are for special projects, the EDF and FIFO policies fulfil a higher percentage of the total demand, and with less delayed orders. However, when 20% of the orders are for special projects, the SPTF policy achieves a higher percentage of fulfilled demand, followed by the FIFO and PB-EDF policies. The results obtained when there is demand for special projects are not as easily interpretable; however, a general decrease in the percentage of fulfilled demand for ETO products with the increase in the percentage of demand for special projects is verified. This also leads to a higher percentage of delayed deliveries at the level of the MTO orders. Despite this, there is no single policy that outperforms the remaining.

The results obtained show that it is impossible to identify a single queuing policy that performs best in all performance measures, under all circumstances. This agrees with the literature (Gupta and Sivakumar 2006). Also, results become less related to the existing literature, and more difficult to assess when the effects of the demand for special projects are considered. The performance of all queuing policies tends to degrade as demand for special projects increases. This may be due to an overall workload increase and the higher uncertainty induced in the system by the new product development process, e.g. as in the variable time of releasing the special projects for production at the shop floor, resulting from different availability of the developers or errors occurring during project development.

Table 2. Percentage of fulfilled demand and percentage of delayed deliveries in the simulation period, for the different queuing policies and for the different demand patterns.

		No SP	**10% SP**		**20% SP**	
			Standard Products	**Special Projects**	**Standard Products**	**Special Projects**
EDF	% fulfilled demand	100,0	100,0	70,0	100,0	47,6
	% delayed deliveries	19,8	19,8	71,4	41,9	90,0
FIFO	% fulfilled demand	100,0	100,0	70,0	100,0	57,1
	% delayed deliveries	43,0	50,0	71,4	69,8	91,7
SPTF	% fulfilled demand	100,0	100,0	60,0	100,0	61,9
	% delayed deliveries	30,2	40,7	83,3	51,2	92,3
PB-EDF	% fulfilled demand	100,0	100,0	60,0	100,0	57,1
	% delayed deliveries	10,5	14,0	83,3	29,1	83,3

Effect of process parameters on selected performance measures – DOE

In the second stage of the model application and output assessment, the goal is determining the system parameters, related to the human resources and the project development influencing the performance of the system. To conduct the analysis we used full factorial design methodology of DOE (Antony 2014) to create the simulation input parameters and assess the model results. We considered the effects of four parameters, at two levels – low and high – as in Table 6 in Appendix 1. The selected parameters are human resources and project development related.

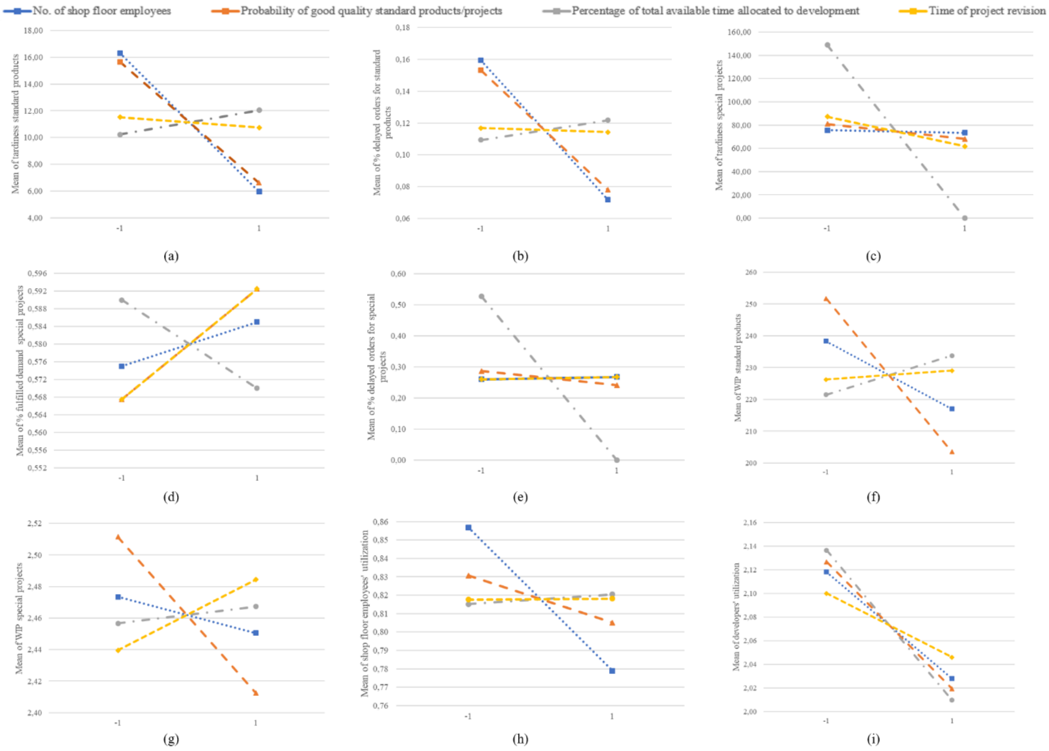
Figure 8 presents the main effects plots for the mean response values of the different performance measures, to the system parameters. On one hand, higher curve magnitude represents a stronger impact; on the other hand, the sign of the main effect shows if the average performance value increases or decreases. The Pareto plots of the factor effects are presented in Figure 9. These plots allow detecting the parameter and interactions effects which are most relevant to the system under study. Any parameter extending beyond the vertical reference line is potentially relevant for the system.

From the analysis of the plots results in Figures 7(a) and 7(b), the number of shop floor employees and the probability of good quality standard products/projects have the stronger impact in the tardiness of the standard products and the percentage of delayed orders for the standard products, with the mean performance response increasing with a decrease in these parameters. The Pareto charts in Figure 9(a) and 9(b) show multiple parameters and interactions being relevant for the system. The mean tardiness of the special projects is predominantly affected by the percentage of total available time allocated to development, Figure 8(c), and the Pareto chart, Figure 9(c) shows that the time of project revision and the interaction between the percentage of total available time allocated to development and the time of project revision should not be neglected. The mean percentage of fulfilled demand for special projects, Figure 8(d) shows that the superimposed curves of the probability of good quality standard products/projects and time of project revision are the most influential, while the Pareto chart in Figure 9(d) shows that the interaction between the probability of good quality standard products/projects and the percentage of total available time allocated to development should neither be neglected. The percentage of delayed orders for special projects is predominantly influenced by the percentage of total available time allocated to development, Figure 8(e), with this parameter being the only extending beyond the reference line in the Pareto chart in Figure 9(e). The WIP levels for the standard products are mostly influenced by the probability of good quality standard products/projects and the number of shop floor employees, Figure 8(f), yet other parameters and their interactions should not be neglected, Figure 9(f). The WIP of the special projects, Figure 8(g) is mostly influenced by the probability of good quality standard products/projects, but other factors' interactions should not be neglected, Figure 9(g). The shop floor employees' utilization is mostly affected by the number of shop floor employees and the probability of good quality standard products/projects, as in Figure 8(h); however, other parameters and interactions should not be neglected, Figure 9(h). Finally, Figure 8(i) and 9(i) show that none of the considered parameters is particularly relevant for the developers' utilization.

Overall, the performance measures related to special projects are mostly influenced by parameters directly related to the project development, as the percentage of total available time allocated to development and time of project revision. For standard products, the most relevant parameters are at those related to the shop floor, as the number of shop floor employees and the probability of good quality standard products/projects. From a practical perspective, this implies that environments combining MTO and ETO strategies should entail a close monitoring at the shop floor and product development levels, and not solely focusing in one of them, so better performance levels can be achieved.

Conclusions, improvements and future research directions

In this work, we presented a hybrid SD-DES-ABS conceptual model framework for jointly analysing the development/customization, production, resources allocation and management tasks in MTO/ETO environments. This framework is useful for predicting the performance of the system under different demand patterns and different operating policies, and assessing the system parameters that have most influence in performance.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 8. Main effects plots for the effects of the process parameters in the different performance measures. (a) Tardiness standard products; (b) % delayed orders for standard products; (c) Tardiness special projects; (d) % fulfilled demand for special projects; (e) % delayed orders for special projects; (f) WIP standard products; (g) WIP special projects; (h) Shop floor employees' utilization; (i) Developers' utilization.

The complexity of combined MTO/ETO environments calls for the use of simulation for performance assessment. The different nature and variety of problems that can arise in these environments demand using different approaches for analysing problems in different dimensions, but occurring in the same production environment. On one hand, project development activities, capturing dynamic behaviour, with multiple project revisions and rework activities are better represented by a SD model. Production activities, with detailed routing of components in the shop floor and production policies implementation are better captured by a DES approach; and, human resources, particularly knowledge resources, are better simulated as agents, whose internal state affects the system performance. A hybrid simulation framework allows modelling complex and varied sub-systems interacting, without falling into cumbersome and improper use of methods, while taking advantage of the different methods' features.

Even though the simulation framework is valuable for performance assessment in combined MTO/ETO strategies, it only has been applied to a case study company. For the case study company, tardiness, WIP, human resources utilization, and percentage of late deliveries have been assessed for different queuing policies in the shop floor. The results obtained when only demand for standard products is considered are aligned with the existing literature, however, when orders for special projects are considered results become more uncertain and difficult to assess. Obtained performance measures tend to degrade with the increase in demand for special projects. Several reasons may lead to this performance deterioration, as the variable time of releasing the special projects for production at the shop floor, resulting from different availability of the developers or errors occurring during project development. Also, operational parameters at the shop floor are most relevant for performance measures related to the standard products, while for special projects, parameters related to project development are more relevant.

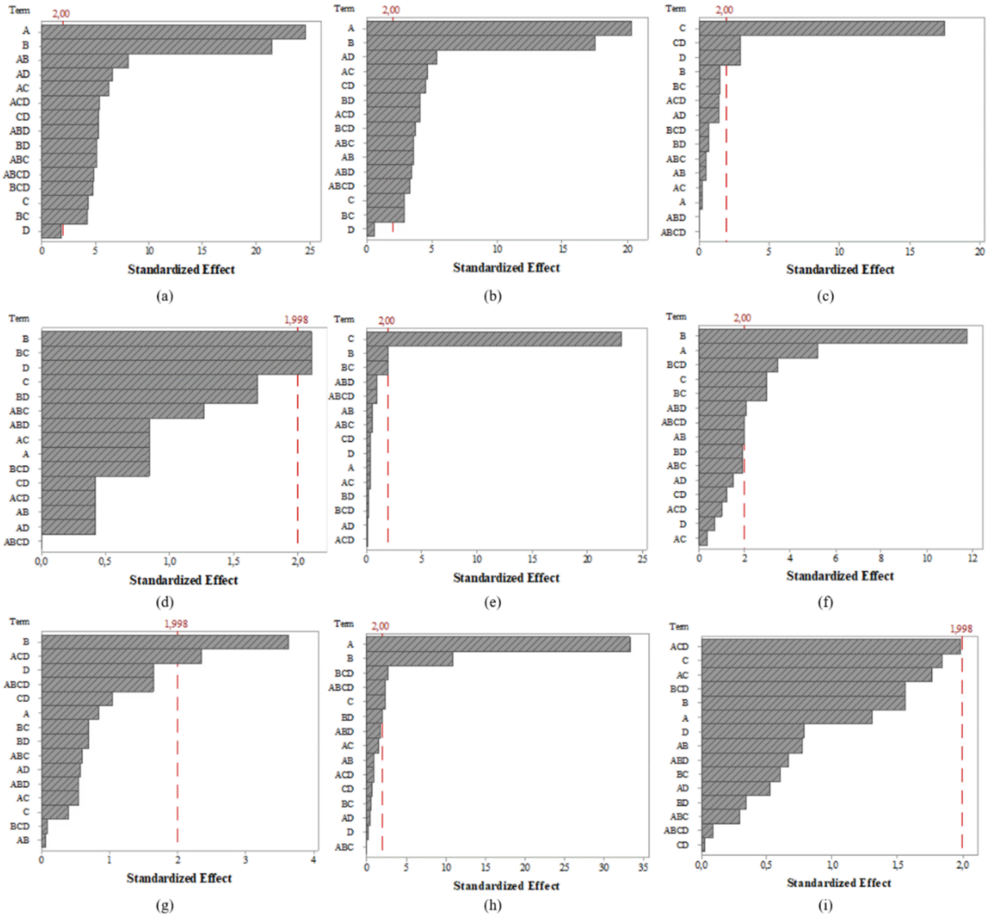

A: Number of shop floor employees; B: Probability of good quality standard products/projects; C: Percentage of total available time allocated to development; D: Time of project revision

Figure 9. Pareto charts of the effects for the parameters and their interactions on the performance measures. (a) Tardiness standard products; (b) % delayed orders for standard products; (c) Tardiness special projects; (d) % fulfilled demand for special projects; (e) % delayed orders for special projects; (f) WIP standard products; (g) WIP special projects; (h) Shop floor employees' utilization; (i) Developers' utilization.

Generalization of the use of the framework is not possible at this stage, as it only has been applied to one case study. The results obtained are specific for the selected industrial case company. However, in view of the great resemblance between the selected case company and the literature features of MTO/ETO, the results obtained are still pertinent and a link between the results obtained and the existing literature is established. Also, further improvements to the models could be considered for increased accuracy of the results and resemblance to real systems. Future work should include improving the model e.g., by considering the different stages of the product development process, instead of the aggregated view herein assumed, consider the shop floor employees as agents, instead of entities, include a cost assessment model; and analysing the effect of more system parameters in performance and other operating policies.

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Appendices

Table 3. Processing time average and standard deviation (Std.), in minutes, for each component in the different product families and WC routing order for each product in the different WCs.

			Product Family						
			A	B	C	D	E	F	G
WC1	Processing Time	Average	5	2	7	5	Compound product: 1A+2B	Compound product: 2A+3D	Compound product: 1A+2D+1C
		Std.	1	1	1	1			
	Order		1	1	1	1			
WC2	Processing Time	Average	20	12	30	-			
		Std.	3	2	3	-			
	Order		2	3	3	-			
WC3	Processing Time	Average	4	5	2	3			
		Std.	1	2	1	1			
	Order		4	4	4	2			
WC4	Processing Time	Average	3	5	6	-			
		Std.	1	2	1	-			
	Order		3	2	2	-			
WC5	Processing Time	Average	10	13	9	4			
		Std.	3	4	2	1			
	Order		5	5	5	5			
WC6	Processing Time	Average	8	4	8	7			
		Std.	2	1	2	2			
	Order		6	6	6	6			

Table 4. Average and standard deviation (Std.) processing times, in days, for the special projects in each WC.

	WC1	WC2	WC3	WC4	WC5	WC6
Average	6	9	8	5	7	6
Std.	2	4	2	1	2	2

Table 5. Process parameters data, where M1 represents machine type 1, M2 represents machine type 2, M3 represents machine type 3, M4 represents machine type 4, M5 represents machine type 5, M6 represents machine type 6, M3.1 represents machine type 3 used in special projects, and M4.1 represents machine type 4 used in special projects.

Resources data	
Initial number of new project developers	3
Initial number of experienced project developers	9
Productivity of new project developers	0.9
Productivity of experienced project developers	0.95
Rate of developers becoming experienced	0.1/week
Quit rate new developers	0.1/month
Quit rate experienced developers	0.5/year
Number of shop floor employees	14
Number of machines	M1 – 2; M2 – 4; M3 – 1; M4 – 1; M5 – 3; M6 – 2; M3.1 – 1; M4.1 – 1
Machine time to failure (months)	M1 – 2; M2 – 1.5; M3 – 3; M4 – 1.5; M5 – 2; M6 – 3; M3.1 – 3; M4.1 – 1.5
Machine time to repair (minutes)	M1 – 60; M2 – 60; M3 – 60; M4 – 60; M5 – 60; M6 – 60; M3.1 – 60; M4.1 – 60
Machine time to next failure (weeks)	M1 – 4; M2 – 4; M3 – 4; M4 – 4; M5 – 4; M6 – 4; M3.1 – 4; M4.1 – 4
Probability of good quality standard products	95%
Probability of good quality special projects	98%
Product Development data	
Scope of project revision	10% of initial project workload
Time of project revision	First revision – ½ of the initial project schedule; Other revisions – every 250 hours of work.
Rejection normal	5%
Percentage of total available time allocated to development	25%
Initial level of available materials in each project	1.5*initial project workload
Workforce Management data	
Desired utilisation of project developers	0.7
Maximum number of project developers	20

Table 6. Low and high levels of the parameters used in the study of the impact in performance measures

Parameter	**Low (-1)**	**High (1)**
Number of shop floor employees	14	16
Probability of good quality standard products/projects	90%/95%	95%/100%
Percentage of total available time allocated to development	25%	30%
Time of project revision	First revision – ½ of the initial project schedule; Other revisions – every 350 hours of work.	First revision – ½ of the initial project schedule; Other revisions – every 250 hours of work.

Paper D

Towards a hybrid multi-dimensional simulation approach for performance assessment of MTO and ETO manufacturing environments

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Abstract - Despite the growing relevance of customization as a source of competitive advantage, the make-to-order (MTO)/engineer-to-order (ETO) manufacturing strategies have been neglected in the literature. Companies following these strategies deal with simultaneous customer-oriented projects that compete for and share resources, while coordinating interdependent engineering and production activities. It becomes relevant understanding the impact that different development projects and production variables have on the manufacturing system performance. For this, we propose a hybrid multi-dimensional simulation model, using System Dynamics (SD), Discrete Event Simulation (DES) and Agent-based simulation (ABS) for MTO/ETO performance assessment.

Keywords - Engineer-to-order; Hybrid simulation; Make-to-order; Performance

1. Introduction

Make-to-order (MTO) and engineer-to-order (ETO) manufacturing environments are challenging. In MTO, the product to be manufactured already exists at the order entry moment [1] and, in ETO, the customers require products designed to satisfy their needs [2, 3]. In MTO and ETO, there are long lead times, variable product demand and product specifications, and process durations [4], low production volumes and high variety of products. Development activities play a key role in adapting existing designs or creating completely new product designs [3] and serving as an order winner for MTO [1]. Most ETO manufacturers generate the main share in their revenues from MTO products [1]. Companies following these production strategies deal with simultaneous customer-oriented projects that compete for and share resources [5], and with each new product design being the result of the execution of a project [6].

In these environments, product development and production are interdependent, and engineering revisions are handled through manufacturing. Coordination between engineering and manufacturing is key to fulfil customer orders [3]. In this work we intend to simulate the influence of the development activities in the MTO/ETO supply chain (SC) performance. Also, we intend to assess the influence of development and production key variables on performance.

Simulation modelling is often an alternative for analyzing complex manufacturing systems [7] and given the different nature of the processes involved in the MTO/ETO SCs, we propose a hybrid simulation model, using different simulation methods: System Dynamics (SD), Discrete Event Simulation (DES) and Agent-based simulation (ABS). In the proposed approach, value chain actors are represented as agents. Development activities are simulated using SD and production and commissioning using DES. Planning and coordination activities are developed through different business rules (heuristics). The simulation model is applied to case of an advanced manufacturing company.

From this work is possible to understand the impact of development projects and production variables on the MTO/ETO system performance. Variables as engineering design workload, type of project, design reuse, components in outsourcing, complexity of design, and experience and knowledge of the technology used in the project, are investigated. SC performance metrics are quantified, and the influence of the variables assessed.

Despite the relevance that coordination between development and production activities has, and apart from works addressing the dynamic simulation of new product development [8] and the engineering change management process [9], the engineering activities have been neglected and works addressing the simulation of development and production activities at the value chain level are not common [10]. In this work we attempt to bridge this gap.

The paper is organized as follows: section 2 introduces the relevant variables during the initial order assessment that will be investigated through the simulation model and relevance of simulation as a performance assessment tool; in section 3, the simulation model is explained, along with a justification for the methods used; section 4 presents the model results and the discussion; the paper ends in section 5, with the conclusions and future research directions.

2. MTO and ETO performance assessment

2.1. Relevant determinants for product design and development during initial customer order assessment

Assessing the impact of interrelated product development and production activities is critical given the many engineering changes that occur during production [11], the complex product structures with many assembly levels [12], the different design options – design from scratch or using existing designs [11, 13], and the volatility of the workflow [14]. Taking into account the different relevant dimensions that we can consider in this domain, we identified six product design and development determinants that can be used during the customer order assessment and that will be integrated in the proposed model.

- Design/engineering workload – Customization and engineering tasks demand diverse design/engineering efforts [15]. This translates in different workloads for customization and number of design objects to be considered.

- Project type –Depending on the type and number of products to be integrated, the process workflow becomes volatile, and the speed of development is affected. Gosling, Naim et al. [14] identified the volatility of workflow and speed of construction as SC uncertainties associated to the process.

- Design reuse – This determinant represents the percentage of sub-systems/components whose design will be reused. Products that don’t belong to a company portfolio can require minor adjustments or major structural changes [15], with the engineering activities starting from an existing design or from scratch [11].

- Outsourcing – Suppliers play a key role in SC uncertainty in MTO and ETO, with supplier early and late deliveries being critical [14]. The percentage of components in outsourcing is a relevant determinant in the SC performance.

- Complexity – Products resulting from ETO projects are complex with many assembly levels [12], with costly design alterations made late in the pipeline [13]. The complexity of the product plays a critical role in the product integration challenges, the need for rework due to quality problems and the assembly difficulty.

- Experience/knowledge of technology – Technology risk [14] and knowledge reuse [16] are important in the ETO projects execution. Experience/knowledge of technology will impact the deviation of the rate at which design, and engineering tasks will progress and the alterations in the project design and scope.

2.2. Hybrid modelling and simulation and performance assessment

Simulation has been thoroughly used for manufacturing and logistics performance analysis. Unlike mathematical programming methods or stochastic models, simulation allows users assessing the dynamic behaviour of a system [17]. It is the most efficient method for dealing with stochastic variables in a SC [18], and the most effective way for assessing and analyzing the performance and designs of SCs [19]. The testing of different SC strategies becomes possible using simulation, by considering the chains’ feedback loops and delays [20]. Yet, due to the complexity of modern manufacturing, even simulation models can become cumbersome, hindering the analysis of the dynamics of systems. Hybrid modelling and simulation is often used for exploring the potential of combining the strengths of different simulation methods and reducing the complexity of the simulation models [20], by not incurring in improper use of each modelling method. Hybrid simulation considers the use of at least two of three simulation methods: System Dynamics (SD), discrete event simulation (DES) and agent-based simulation (ABS) [21].

Considering the above features of hybrid simulation, and the different nature of the processes involved in the MTO/ETO SC [10], we propose a hybrid simulation model for performance assessment of the MTO/ETO SC. Relevant SC metrics assessed in this context include resources utilization, order delays, and order costs.

3. Proposed conceptual model description

In this work we propose a hybrid SD-DES-ABS model for the MTO/ETO SC, shown in Fig. 1. It is an extension to the SC level of the model proposed in [10]. The proposed model meets the needs of combined MTO/ETO manufacturing organizations that engage in product design and development, project planning, manufacturing, assembly, and commissioning. Information and material flows between three SC actors – supplier, manufacturer, and customer - are considered. Each SC actor is an agent whose internal structure entails different modules, as in Fig. 1.

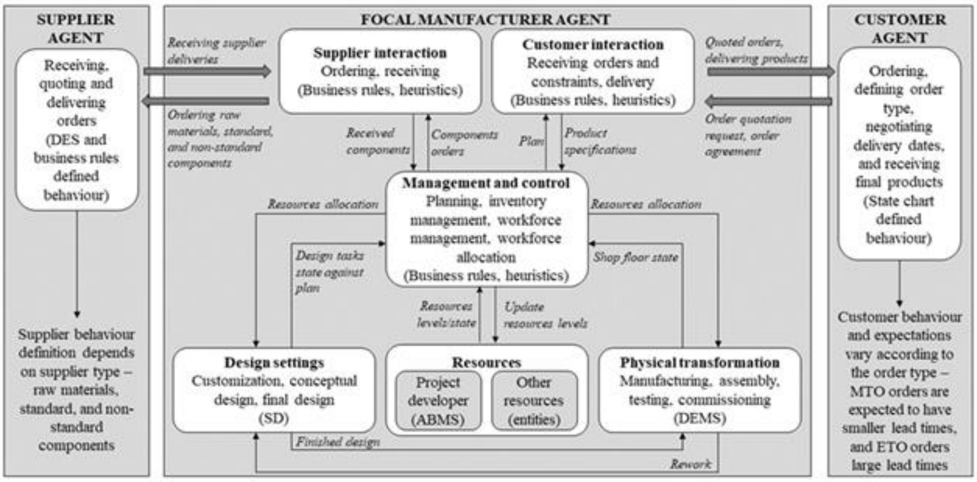


Fig. 1. Conceptual hybrid SD-DEMS-ABMS simulation model for the MTO/ETO SC.

3.1. Supplier agent

Three types of suppliers are considered: raw materials, standard components, and special components. The first supplies raw materials that are transformed by the manufacturer; the second provides standard components used in MTO products, for which lead time is known; the third type is the supplier that designs and manufactures outsourced special components in ETO products. The internal behaviour of the suppliers is defined by a DES model, in which the process delay for the raw materials and standard components is known; for the special components is defined by the supplier, according to the complexity of the ordered components. DES was the selected method given its benefits in representing operational activities [22], tracking of individual items (orders) and assuming variable processing times.

3.2. Focal manufacturer agent

The manufacturer agent is the most complex, entailing activities involved in the supplier and customer interaction, order assessment, management and control of orders, product design, manufacturing, and resources management. The interactions between the manufacturer and the suppliers are triggered by events that are internal to the manufacturer; while the interactions with the customers are triggered by a message being sent by the customer to the manufacturer.

3.2.1. Supplier interactions

Interactions with suppliers depend on the supplier type. Raw materials are ordered regularly, with a known lead time. Standard components are ordered when required for a confirmed MTO order. The special components are first quoted – the number of components to be quoted by the supplier depends on the percentage of outsourced components –, and when the customer confirms the ETO order, the manufacturer gives the confirmation to the supplier to start the manufacturing activities. The special quoted components complexity level will influence their cost and lead time.

3.2.2. Customer interactions

Interactions with customers result from a customer asking an order quotation. When a customer sends a message for placing an order, the manufacturer identifies the type of order (MTO or ETO). After, order assessment and planning occur, and conceptual product design, for ETO orders, the expected delivery time and order costs are sent to the customer. Upon receiving customer confirmation, ordering of standard and special components (when applicable) occur, followed by engineering activities in ETO, production, and product delivery.

3.2.3. Order assessment

During the order assessment, relevant determinants for product design and development are defined. Indices for defining the stochastic model elements for the ETO orders are established. These indices are linked to model variables and influence the outcomes of the project execution. The product design and development determinants have been identified in section 2.1., and in Table 1 we establish the model variables affected by each determinant.

Table 1. Product design and development determinants during initial customer order assessment

Determinant	Model variables affected	Levels considered
Design and engineering workload	Work to be done	Very low, Low, Medium, High, Very high
Project type	Normal design rate	One, two, three, four, five, six
Design reuse	Percentage of components that are designed of the shelf	Very low, Low, Medium, High, Very high
Outsourcing	Percentage of components in outsourcing	Very low, Low, Medium, High, Very high
Complexity	Normal quality rejection rate	Very low, Low, Medium, High, Very high
	Percentage of components with errors detected during assembly	Very low, Low, Medium, High, Very high
	Assembly time	Very low, Low, Medium, High, Very high
	Outsourced components complexity	Very low, Low, Medium, High, Very high
Experience/knowledge of technology	Normal design rate deviation	Very low, Low, Medium, High, Very high
	Change rate to design and change in scope of the project design	Very low, Low, Medium, High, Very high

3.2.4. Management and control functions

Business rules have been used for the management and control functions, that include planning, inventory and workforce management, and workforce allocation.

For planning, a backward approach is used. In MTO, considering the desired delivery week set by the customer, there is an evaluation of the latest possible starting week for manufacturing activities. If manufacturing can start after the current week and delivery is possible in the desired date, the proposal is sent to the customer; otherwise, a forward approach is considered and the earliest possible delivery week, considering the manufacturer available capacity, is proposed to the customer. A similar approach is used for the ETO; however, planning occurs only after preliminary design activities have occurred. Re-planning occurs when the customers asks for design/engineering alterations.

Inventory management functions include regular monitoring of the raw materials levels and the ordering of standard and special components when needed. Ordering the raw materials considers a safety stock, and a minimum order quantity set by the supplier. Standard and special components are ordered in the number they are needed.

The workforce management function targets the shop floor employees, who are entities in the model. When planning the orders, if in a certain week the resources that are missing to fulfil the order are human resources, then the required number of shop floor employees is temporarily hired.

Workforce allocation functions target the allocation of project developers, who are individual agents, to the projects being handled by the MTO/ETO manufacturer. Project developers can be allocated to MTO orders, when small modifications in components are requested by the customers, or to ETO orders for the design of a new product. In either situation, the developers' state (present, absent, providing support to training tasks) affects the design tasks' progression. The workforce allocation function is executed when a new order enters the system, a project developer quits the job, a project design finishes, or additional design alterations are requested by the customers.

3.2.5. Product design settings

As in [10], each new product was considered a project (and an individual agent), whose design activities have been simulated using SD. The choice of SD as a modelling and simulation tool for the design activities considered the method's capability in representing the dynamic behaviour of factors affecting the project execution, as the rework, change in project scope, quality issues, and productivity [23]. Considering this, we adopted the model proposed by Rodrigues, et al. [8] for simulating the project execution inside the order agent. Variables as the workload, project type, design reuse, complexity, and experience/knowledge of technology will influence the project execution.

3.2.6. Manufacturing, transportation, and commissioning

Manufacturing, transportation and commissioning are simulated using DES, considering the capabilities of the method in representing manufacturing settings [22] and shop floor operations with stochastic elements [7]. For MTO products, shop floor operations are known, while in manufacturing of ETO products, the operations sequence is unknown and randomly attributed during the model run time. For ETO products higher uncertainty is considered for the manufacturing and assembly operations time. The assembly time in ETO depends on the order complexity, established during the order assessment.

3.2.7. Resources

Project developers are the human resources represented as agents. The productivity of each developer depends on its experience. The productivity index for each developer will interfere with the project workflow. Also, experienced developers may aid in training the new developers. During training periods, the experienced developers are not contributing to the projects development. The same is verified when a developer is absent from work.

3.3. Customer agent

The customer agent is the demand driver in the model, and its behaviour is given by a state chart. Each customer can place a MTO or an ETO order. Upon requesting an order quotation, the customer presents an expected delivery date for the order and, when receiving a reply from the manufacturer, with the possible order delivery date, the customer decides whether to accept the terms proposed by the manufacturer. When accepting the manufacturer proposal, a MTO order will proceed to manufacturing; for an ETO order, the customer may require design alterations that can be reflected in new components being designed or altered. When the products have been manufactured, these are delivered and commissioned. The customer can withdraw the request for the order quotation when the manufacturer does not give a response within a reasonable time frame.

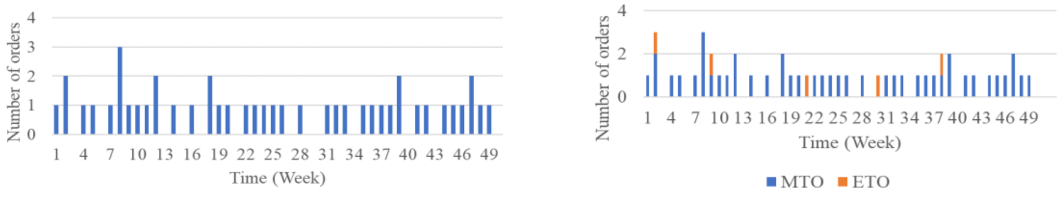
4. The case study company

The case company is an advanced Portuguese company that develops tailored solutions for industrial automation and mechanical engineering. The company produces customized industrial conveyors for the food and chemical industries, robotic arms and palletizers. It produces and sells a wide range of complex, long life cycle products, in low volume. These features associated to highly variable product demand require a SC able to comply with the diverse range of products and dynamic demand. The company is currently employing two manufacturing strategies: MTO and ETO. For standard products, for which small alterations are allowed based on the customers' preferences, the case company employs the MTO strategy; for products designed to unique customer requirements, the case company uses an ETO strategy, starting a new product development project for each new order.

5. Results and discussion

The model was implemented using the Anylogic software. Two scenarios are analysed in the context of this work. In the first the company only receives MTO orders. In the second, ETO projects with different product design and development determinants are considered.

Fig. 2 shows the demand patterns considered for the scenarios; the classification of the ETO projects in scenario 2 is given in Table 2.



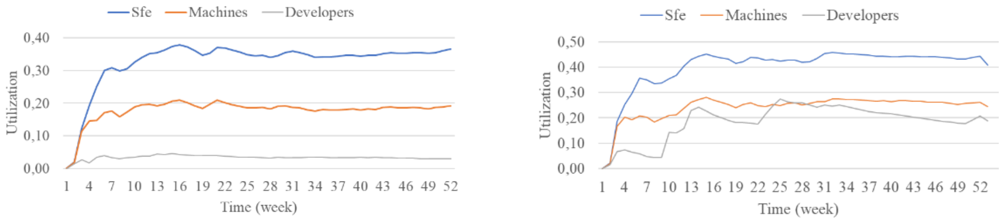
(a) (b)

Fig. 2. Demand distribution. (a) Scenario 1 – only MTO orders; (b) Scenario 2 – Five projects are added to the demand in scenario 1.

Table 2. Project determinants

Project determinant	Project 1 (week2)	Project 2 (week 9)	Project 3 (week 21)	Project 4 (week 30)	Project 5 (week 8)
Workload	Very low	Very high	Medium	Very high	Very low
Design Reuse	Very high	Very low	Medium	Low	High
Outsourcing	Very high	Very low	Medium	Low	High
Complexity	Very low	Very high	Medium	Very low	Very high
Experience	Very high	Very low	Medium	High	Low
Type	1	6	4	5	2

When comparing the results in scenarios 1 and 2, for the resources utilization, in Fig. 3, it is possible to observe a general increase in the utilization of all resources when ETO orders are considered. The highest increase in utilization was registered for the project developers whose average utilization increased 444% from scenario 1 to scenario 2.



(a) (b)

Fig. 3. Resources utilization: Sfe – shop floor employees, M1- WorkCentre 1, M2- WorkCentre 2, M3- WorkCentre 3, M4- WorkCentre 4, M5- WorkCentre 5, M6- WorkCentre 6, Developers- project developers. (a) Scenario 1; (b) Scenario 2.

Table 3 presents the delays in the orders. In scenario 1, no customers are lost, while in scenario 2 one customer is lost; in scenario 2, the number of late and early served customers increases, and the average delay is positive and lower than in scenario 1. The average delay is positive, meaning that in average deliveries have been made later than required by customers.

Table 3. Served customers, lost customers, late customers, early customers, on time customers, and average delay in scenarios 1 and 2.

Scenario	Served customers	Lost customers	Late customers	Early customers	On time customers	Average delay (weeks)
1	44	0	6	0	38	0.14
2	48	1	7	12	29	0.11

The orders costs were divided in different categories, as in Fig. 4. In scenarios 1 and 2, the MTO orders, registered the lowest total costs -the highest percentage of costs is allocated to the shop floor employees; for project one in scenario 2, this is also verified. For project one in scenario 2, the costs with suppliers are similar to the costs with shop floor employees, which may be attributed to the very high level of components outsourcing. The highest percentage of costs in projects two, three, four, and five in scenario 2 is registered for the project developers. In project two, the high percentage of costs with project developers results from the very high workload, very low outsourcing of components, and high project complexity. This is the project with the highest total cost. For project five, despite the very low workload and high outsourcing of components, there is a very high complexity and low experience, that translate in more working hours for the project developers.

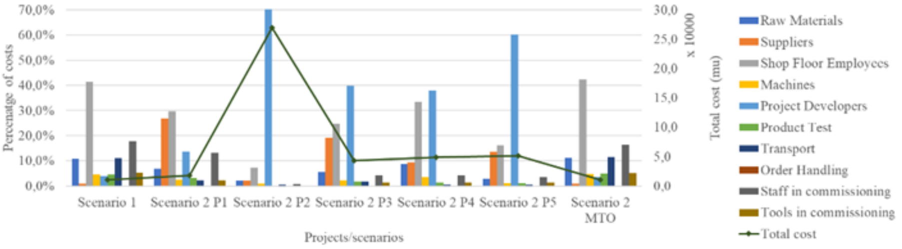


Fig. 4. Percentage of costs in different categories in the scenarios considered, and total project cost.

6. Conclusions and future research directions

In this work, we proposed a hybrid SD-DES-ABS simulation model for performance assessment of the MTO/ETO SC. The complexity of these SCs, and the different processes involved call for different simulation methods to represent each process. Despite the broad context of application of the simulation model, it only has been applied to one case study company. The obtained performance measures tend to worsen when ETO orders are considered, with a substantial increase in the resources utilization – with the highest increase to the project developers – and less customers being served on time. Also, the costs distribution in MTO and ETO orders vary significantly.

Future work should consider comparing the results with existing literature, and a more thorough analysis of the results and an assessment of the model variables that are the root causes of the different performance levels registered. Additionally, an improved description of the model is required, alongside a detailed report of the model variables that are affected by the identified performance determinants. The model should be validated to other application domains.

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Paper E

Assessing the impact of performance determinants in complex MTO/ETO supply chains through an extended hybrid modelling approach

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Abstract - In make-to-order (MTO)/engineer-to-order (ETO) business environments multiple customer-oriented projects compete for and share resources through interdependent engineering and production activities. Deep knowledge of critical dimensions that affect performance is key in this context. For this, we propose a set of determinants - workload, complexity, outsourcing, design reuse, project type, and knowledge/experience with technology, that impact performance. These determinants are input to an extended hybrid simulation model using System Dynamics (SD), Discrete Event Simulation (DES) and Agent-based simulation (ABS) that tackles the needs imposed by activities of very different nature, as the project development and manufacturing/assembly operations. The hybrid model is applied to the case of an advanced manufacturing company. Through Monte Carlo sampling, the influence of different combinations of determinants in the performance variability is assessed. A correlation analysis shows evidence of association between all performance determinants and the project time and cost, while no evidence of association between the design reuse and project type determinants and the manufacturing and assembly time.

Keywords - Correlation; Hybrid simulation; Mote Carlo; MTO/ETO supply chain

Introduction

Make-to-order (MTO) and engineer-to-order (ETO) supply chains have been given more relevance in the past years as a result of increasing customer requirements for more customized products (Adrodegari et al. 2015). These supply chains are interrelated, with most ETO manufacturers engaging not only in producing products that require customer input, but also in manufacturing portfolio products to order, from which they earn most of their revenues (Willner et al. 2014).

Key to the performance of these chains are product design and customisation. In a MTO strategy, demanded products are configured according to pre-defined attributes, and customers' choices are restricted to limited options. MTO supply chains respond to deterministic yet uncertain demand (Sahin and Jr. 2005). These supply chains are vulnerable to demand uncertainty, disruptions in material supplies, long product lead times, and large order backlogs. In the ETO supply chain, unique and complex products are designed and produced to the customers specifications. Each product is managed as a project, with the customer influencing the design of the product (Rudberg and Wikner 2004; Gosling, Naim, and Towill 2013). ETO supply chains must be flexible, manufacturing in low volume (Rudberg and Wikner 2004).

Critical activities in MTO and ETO companies include tendering, planning, contact with suppliers, engineering design, manufacturing, assembly, and commissioning (McGovern, Hicks, and Earl 1999). Companies following these strategies deal with varying projects' complexity (McGovern, Hicks, and Earl 1999), and engineering changes being handled through manufacturing. Yet, as previously referred by Hendry (2010), there is lack of approaches focusing and addressing the needs of MTO and ETO environments. Managerial paradigms successfully applied to other environments are not applicable, given the many projects carried at the same time, at different stages, with different completion levels and subject to frequent changes (Adrodegari et al. 2015). Critical and bottleneck activities, the engineering activities (Grabenstetter and Usher 2015), are seldom included in existing supply chain models. These activities are a source of complexity and uncertainty in MTO/ETO and should be carefully planned and managed.

Considering the above, we study the influence that engineering activities have in the MTO/ETO supply chains. Also, we intend to assess the influence of different performance key determinants on the supply chain performance. We propose a hybrid simulation approach including engineering and manufacturing/assembly activities and integrating three simulation methods: System Dynamics (SD), discrete event simulation (DES), and agent-based simulation (ABS). The proposed model is an extension to the supply chain level of the model proposed in (Barbosa and Azevedo 2018). In the proposed approach, the supply chain actors are agents, whose internal structures include different decision and transformation processes. The development activities are simulated using SD and production and commissioning are simulated using DES. The planning and coordination activities are business rules (heuristics). A Monte Carlo sampling method is used to assess the impact of different model input parameters in the model performance measures. The simulation model is applied to case of an advanced manufacturing company.

The proposed model allows assessing the influence of different project and production determinants, as the engineering design workload, the project type, the design reuse, components in outsourcing, complexity of the design at the project level, and experience and knowledge of the technology used in the project. Different supply chain performance metrics are quantified, and the influence of the performance determinants assessed.

The remaining of the paper is organised as follows: section 2 presents the state of the art of the MTO and ETO supply chains and summarizes the determinants used during order assessment that will influence the system performance. Section 3 delves on identifying key issues in modelling the MTO and ETO supply chains and justifies the use of a hybrid simulation approach. Section 4 presents a detailed description of the proposed model, and section 5 describes the model implementation. Section 6 presents the results and discussion, and the paper ends in section 7, with the conclusions and future research directions.

Performance determinants in MTO and ETO supply chains

Companies operating under the MTO/ETO strategies deal with simultaneous projects that compete for and share resources (Alfieri, Tolio, and Urgo 2012). These supply chains are not mutually exclusive. ETO organizations often earn most of their revenues from MTO products (Willner et al. 2014). As previously noted by Adrodegari et al. (Adrodegari et al. 2015), frameworks for managing the ETO environment can be derived from MTO, as the first is an extension of the second, with the addition of design and engineering processes.

In organizations following MTO and ETO strategies, complex combined production environments can be observed, involving many processes and resources, and encompassing many possible problems. Considering this, different critical determinants can cause performance variations in these supply chains.

MTO and ETO supply chains operate in low volume and high mix production (McGovern, Hicks, and Earl 1999; Stavrulaki and Davis 2010; Mello, Strandhagen, and Alfnes 2015). Relevant features of these environments include different customization levels, long lead times, variable product demand and specifications, and variable processes durations (Hicks and Braiden 2000). There are three main sources of uncertainty in these environments: customers, manufacturers, and suppliers (Gosling, Naim, and Towill 2013). On the demand side of these supply chains, uncertainty is a consequence of high unpredictability and volatility of customer orders (Sahin and Jr. 2005; Adrodegari et al. 2015). While in MTO, this results from the product customization that is allowed based on pre-existing product design specifications and standard modular components (Stavrulaki and Davis 2010), in ETO, future orders represent unknown product specifications (McGovern, Hicks, and Earl 1999; Akinc and Meredith 2015), lead times for supply and delivery, and duration of the production processes (Adrodegari et al. 2015). The ETO supply chain is characterized by high levels of product customization and is usually managed in a project environment (Gosling, Naim, and Towill 2013). In MTO, production does not start until the order has been confirmed (Stavrulaki and Davis 2010). For this, after an order has been confirmed, and despite a certain degree of customization being allowed, most processes are concerned with manufacturing and assembly of the final product (Hendry 2010). This does not apply to ETO products. The order decoupling point is at the design stage, and the customer influences the design of the product (Gosling and Naim 2009), and is exposed to the entire order lead time, including conceptual and detailed design, procurement, manufacturing, assembly, testing, and commissioning. Design, manufacturing, and assembly occur after the order has been confirmed (Hendry 2010; Caron and Fiore 1995). Other processes include equipment installation and commissioning. ETO companies are characterized by projects that are limited in time and include the above-mentioned specialized functions (Caron and Fiore 1995). The engineering process is a bottleneck core process (Grabenstetter and Usher 2015). Delivery dates are often estimated ignoring information about capacity constraints because it is common for several quotations to be waiting for potential customer responses. This requires reviewing delivery dates upon order acceptance (Hicks, McGovern, and Earl 2000).

These manufacturing environments are very complex. In ETO, complexity results from complex product structures (Mello, Strandhagen, and Alfnes 2015; McGovern, Hicks, and Earl 1999), that require many levels of assembly (Mello, Strandhagen, and Alfnes 2015), the mix of demand volumes for different components, the various production methods (McGovern, Hicks, and Earl 1999), production planning, costing and shop floor control (Adrodegari et al. 2015), and lack of information due to overlap in design and manufacturing activities (McGovern, Hicks, and Earl 1999). Incomplete engineering activities before production lead to many errors and engineering revisions (Mello, Strandhagen, and Alfnes 2015). Components and sub-systems in ETO products may be re-engineered for each sales order. These are very expensive products and customers are usually industrial customers and not consumers (Lu, Petersen, and Storch 2009).

From one order to another, ETO products can include different degrees of standardized and customized components (Gosling and Naim 2009). While some product components are newly designed and engineered, others are predefined. This entails different design and engineering effort from one order to another (Lu, Petersen, and Storch 2009). Different degrees of customization and knowledge reuse will have a direct impact on the order lead time (Mourtzis et al. 2014; Henrique, Ola, and Erlend 2015). The higher the customization degree, the higher is the expected lead time, because more activities must be performed after an order is received (Henrique, Ola, and Erlend 2015). Capturing knowledge allows learning from previous experiences and making predictions about future outcomes (Addo-Tenkorang et al. 2016).

ETO manufacturers increasingly rely on outsourcing (Hicks, McGovern, and Earl 2000) to reduce costs and lead times (Hicks, McGovern, and Earl 2001). Production can be outsourced, which requires good coordination between engineering and design (Henrique, Ola, and Erlend 2015). Outsourcing decisions and relationship with supplying companies should be carefully managed. Managing inventories in MTO and ETO environments often encompasses keeping high inventory levels to minimize delays (Stavrulaki and Davis 2010). For MTO products, for which the procurement of some components and materials only occurs after an order is received (Amaro, Hendry, and Kingsman 1999), this is critical. ETO companies make procurement decisions at diverse stages of product development. Customers may specify preferred suppliers or present detailed specifications for the products, for which few suppliers can respond. Other parts are only specified at the detailed design stage, which may impact the availability of these parts. For this, parts with long lead-times should be considered in early stages of the design process (Hicks, McGovern, and Earl 2000). Furthermore, and given the relevance of outsourcing in these supply chains, supply uncertainty is critical, as it is an obstacle to the fulfilment of the value-adding activities (Gosling, Naim, and Towill 2013).

Considering the above, we summarize the relevant determinants in the MTO and ETO supply chains in Figure 1. Figure 1 contents build on the assumption that customers, manufacturers and suppliers are the main sources of uncertainty in these manufacturing systems. Also, considering the literature, a set of six performance determinants are considered: complexity, workload, design reuse, project type, outsourcing, and experience/knowledge of technology.

Relevant issues for modelling and simulation of MTO/ETO supply chains

To fulfil the proposed objectives, it is important understanding the structure of the MTO/ETO supply chain, the relevant tasks involved in the operations of these supply chains and the important functions that should be considered in this context. It is also pertinent justifying the use of a hybrid simulation approach to tackle the problematic of performance assessment in these supply chains.

Supply chain structure

In a supply chain in the ETO sector, and as suggested by McGovern, Hicks, and Earl (1999), there are different stages of interaction between the supply chain actors. Two stages of interaction between the manufacturing company and its customers and suppliers can be clearly identified. First, in tendering stage, a conceptual design is developed, and major system components are defined. The selected suppliers are contacted to achieve information about components costs and lead times. Other design and planning activities occur. In a second stage of interaction, that occurs after a contract has been awarded, detailed design and plan are developed, and are followed by component manufacturing, assembly, construction, and commissioning. A third interaction stage with customers has later been considered in Hicks, McGovern, and Earl (2000), in which the manufacturer makes potential customers aware of its products, through marketing strategies. Three stages in the ETO supply chain have also been identified in (Henrique, Ola, and Erlend 2015). These include tendering, engineering, and production, with the possible overlap of the engineering and production stages.

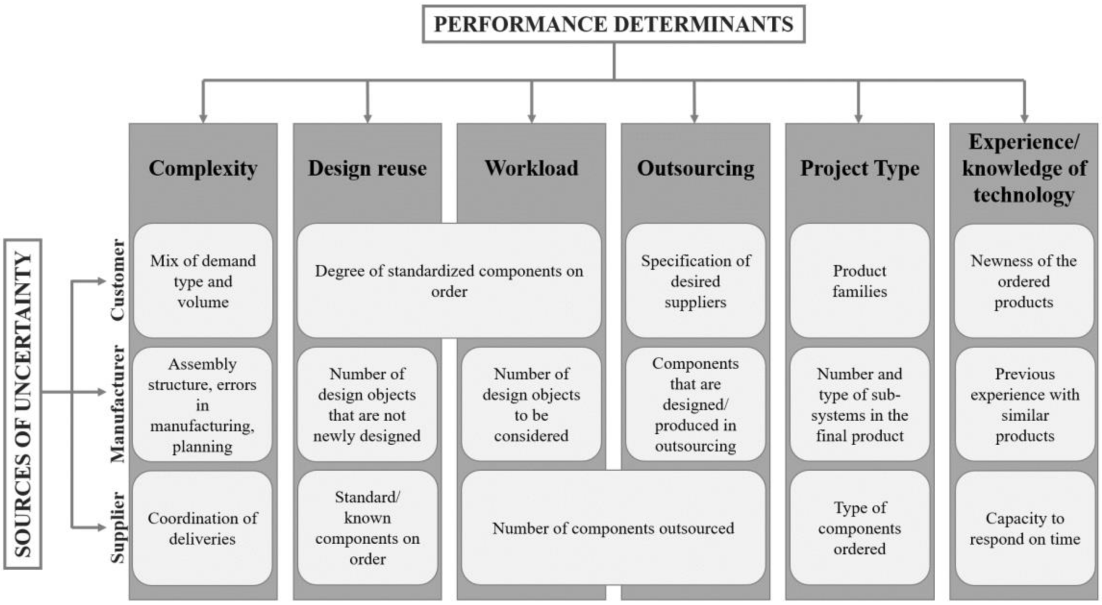


Figure 1. Performance determinants in the MTO/ETO supply chain.

Customers in these supply chains are the demand drivers, by imposing not only the number of products that are manufactured, but also establishing product structures, and configurations (Adrodegari et al. 2015). While in MTO, customers can introduce small product variations, always limited to a set of available options, in ETO the customer sets the complete product specifications. This is the reason why the degree of customisation in an order can vary significantly in these environments (Willner et al. 2014).

Suppliers are key players in the MTO and ETO supply chains. Often, contractual and/or partnership interactions with suppliers are established in this context, with purchasing of materials directly related to a project (Adrodegari et al. 2015). Procurement may occur due to customer specifications, during the tendering stage, or during engineering design (McGovern, Hicks, and Earl 1999).

From the interactions referred in the MTO and ETO supply chains literature, three types of chain actors arise as relevant: customers, suppliers, and manufacturers.

Internal manufacturer requirements

For a manufacturer following an ETO strategy, two types of processes can be identified: non-physical, including engineering design and planning; and physical, including manufacturing, assembly, and installation (McGovern, Hicks, and Earl 1999). Not only design and project management are core competencies in ETO companies (Pandit and Zhu 2007), but also manufacturing, factory-based assembly, testing, construction, installation and commissioning at the customers' sites (Pandit and Zhu 2007; Henrique, Ola, and Erlend 2015). These activities have to be performed for each new product (Adrodegari et al. 2015).

Given the many tasks involved (e.g. requirements gathering, assessing the availability of the components, quoting, assessing feasibility, engineering, and manufacturing), the ETO product development is a time-consuming task. The design stage is seen as a time bottleneck, with the long lead times in ETO often associated directly or indirectly with the design stage

(Amrani et al. 2010). Labour shortages can become a major constraint to the timely execution of the tasks (Gosling et al. 2014).

From the above, a panoply of functions can be identified as critical for the MTO/ETO manufacturer, including design and engineering, planning, procurement/contact with suppliers, manufacturing, assembly, testing, commissioning, and workforce management.

Adequacy of a hybrid simulation approach

Simulation has been thoroughly used for manufacturing and logistics performance analysis. Unlike mathematical programming methods or stochastic models, simulation as a performance analysis tool allows users assessing the dynamic behaviour of the target system under study (Umeda and Zhang 2006). Also, simulation is the most efficient method for dealing with stochastic variables in a supply chain (Lee et al. 2002), and the most effective way for assessing and analysing the performance and designs of supply chains (Rabelo et al. 2015). The testing of different strategies becomes possible using simulation approaches , by considering the chains' feedback loops and delays (Schieritz and Größler 2003).

Given the complexity of modern manufacturing systems, even simulation models can become cumbersome, hindering the analysis of the dynamics of the systems. Hybrid modelling and simulation is often used for exploring the potential of combining the strengths of different simulation methods and reducing the complexity of the simulation models (Schieritz and Größler 2003), by not incurring in improper use of each modelling method. In this work, and as in (Swinerd and McNaught 2012), hybrid simulation approaches are those that use at least two of three simulation methods: SD, DES, and ABS.

Hybrid simulation approaches provide flexibility of analysis (Wang, Brême, and Moon 2014), by overcoming the challenge of representing all system processes under a single method (Sadeghi, Dauzere-Pérès, and Yugma 2016) and allowing extracting the best features of the appropriately chosen methods for the different processes (Brito, Trevisan, and Botter 2011). In the same simulation, different levels of the system aggregation can be simulated (Martinez-Moyano et al. 2007), and the conjoint analysis of the different models' results helps avoiding problems of model consistency, redundancy of components and reducing the model investigation effort (Jacob, Suchan, and Ferstl 2010).

In SD modelling and simulation, feedback loops represent the models' dynamic complexity (Lättilä, Hilletofth, and Lin 2010). The building blocks of SD include stocks, flows, and reinforcing and balancing feedback loops. Finite differential equations establish the interactions between the represented systems (Sterman 2000). SD models are deterministic, for which they do not require multiple iterations (Heath et al. 2011). While SD models excel at a high abstraction level representation of the systems (Borshchev and Filippov 2004), their continuous nature impedes the representation of discrete events (Jovanoski et al. 2012), and their determined structure reduces the model flexibility (Schieritz and Größler 2003).

DES considers the system modelling from a macroscopic point of view (Wang, Zheng, and Zhao 2013), with entities, passive objects, flowing through blocks of activities, suffering delays, waiting in queues, being processed, seizing, and releasing resources (Borshchev and Filippov 2004). The use of this simulation method is advantageous for representing the operational level of organizations (Jovanoski et al. 2012).

ABS is useful for representing dynamic and adaptive systems (Hao and Shen 2008), a feature that well complements the determined structure of SD models (Schieritz and Größler 2003). ABS models use as many details as possible for representing features of the modelled systems (Martinez-Moyano et al. 2007). The behaviour of a system in an ABS model results from the interactions that exist between agents in the environment and from their interaction with the environment. These interactions are governed by logic rules (Wang, Zheng, and Zhao 2013).

Considering the variety of problems that can be addressed through simulation modelling, each modelling method should be used appropriately, by considering its capabilities and the abstraction level of the functions that should be modelled. Given the model proposed in (Barbosa and Azevedo 2018) and considering the work by Borshchev and Filippov (Borshchev and Filippov 2004), in which the authors presented the different applications of simulation modelling, and the simulation modelling methods, associated to an abstraction level scale, and the variety of functions and supply chain interactions that exist in the MTO/ETO sectors, Table 1 summarizes the methods selected to model each function. In the proposed approach, simulation models are considered alongside with heuristics and business rules to achieve coordination between the supply chain functions.

Table 1. Relevant functions in the MTO/ETO supply chains and simulation methods considered

Relevant function	**Correspondence with applications of simulation modelling in Borshchev and Filippov (2004)**	**Abstraction level**	**Selected modelling method**
Engineering/design	R&D project management	Middle to high	SD
Manufacturing, assembly, testing, and commissioning	Factory floor	Middle to low	DES
ETO supply chain members	Supply chain	Middle	ABS
Knowledge resources (project developers)	Individual behaviour	Low	ABS
Workforce management	Manpower & Personnel	High	Business rules (heuristics)
Planning	-	-	Business rules (heuristics)
Contact with suppliers	-	-	Business rules (heuristics)

The extended hybrid model

The proposed hybrid MTO/ETO supply chain model is presented in this section and is an extension to the supply chain level of the model in Barbosa and Azevedo (2018). Within the proposed model, material and information flows between the supply chain actors are included. Following the idea proposed by Schieritz and Größler (2003), each supply chain actor is represented as an agent. Unlike in the initial idea proposed in Schieritz and Größler (2003), the agents' internal processes not only are modelled using SD, but also DES, and business rules (heuristics). Considering the state of the art in sections 2 and 3, the supply chain actors involved are first identified; afterwards, the material and information transfer functions are specified, alongside the constraints involved in the operations and communication processes. The proposed model is tailored to meet the needs of combined MTO/ETO manufacturing organizations that engage in product design and development, project planning, manufacturing, assembly, and commissioning activities.

Model structure

The following supply chain actors are included in the model:

•Raw materials supplier – provides raw materials for transformation at the focal manufacturer.

•Standard components supplier – provides components of the shelf, used in products that are part of the focal manufacturer portfolio.

•Non-standard components supplier – provides components that the focal manufacturer is not capable of producing internally in newly designed products.

•Focal manufacturer – designs, customizes, produces and commissions the final products; engages in planning, inventory, and workforce management activities.

•Customer – places the orders to the focal manufacturer and is the final user of the product.

The focal manufacturer is the key supply chain actor, binding itself to communication and material processing activities, while the remaining members are mostly concerned with material processing. It receives orders from customers, orders to suppliers, manages new product development processes, manufactures and tests the end products, and manages workforce and inventory levels. The internal behaviour of the supplier and customer agents is simpler. Suppliers receive, plan, manufacture and deliver materials/components; customers order products, withdraw orders, accept/reject the manufacturer's proposal, ask for design alterations, and receive the final product and the commissioning team.

Communication between supply chain agents

Communication is a key process in supply chain management for the synchronization of the different processes involved (Umeda and Zhang 2006). A coordinated supply chain improves the overall performance of the individual supply chain actors, by effectively using resources and capabilities, and by measuring the performance of tasks as logistics, inventory management, and supplier and customer relationship management (Maestrini et al. 2017).

In the extended model, communication is established externally and internally to the focal manufacturer. Externally, communication exists between the focal manufacturer and the suppliers, and the customer; and internally, communication is established between different functions for product design and manufacturing management. Following we specify the communication mechanisms, stages, and constraints at the agents' external and internal levels. Figure 2 presents, through a sequence diagram, the communication between the supply chain agents and the sequence of execution of functions in the model.

As presented in Figure 2, the customer is responsible for triggering the execution of the model functions. It specifies the order type – MTO or ETO. For MTO orders, the customer specifies the product type, and the components to be customized, if any, and the preferred delivery date. For ETO orders, the customer specifies all the product requirements and provides information for the manufacturer to develop the product. The manufacturer makes an initial conceptual design of the product that is subject to approval and alterations by the customer. A delivery date is also agreed. Upon acceptance of the conceptual design, the manufacturer proceeds to the technical product design and manufacturing, with some interaction stages with the customer, during which alterations to the design may occur. When the manufacturing, assembly and testing of the product are finished, the focal manufacturer sends the product to the customer through a commissioning team. During order quotation, if the manufacturer does not provide a reply to the customer in acceptable time, the customer may withdraw the request for the order quotation.

For the manufacturing operations at the focal manufacturer, raw materials are needed for components' production. Following inventory management policies, the focal manufacturer places raw materials orders, and the supplier, after order processing, delivers the raw materials at the focal manufacturers' facility. A minimum ordered quantity (MOQ) may be established.

The interaction established between the focal manufacturer and the standard components supplier consists in ordering specific standard components when a MTO order is confirmed. For these standard components, small amounts, as a single unit, may be ordered.

When special critical components are needed for ETO orders, an order for non-standard components is placed. The supplier receives the order from the focal manufacturer, and considering the complexity of the ordered component, informs the focal manufacturer about the expected delivery date and costs. The focal manufacturer assesses the supplier proposal and when receiving confirmation from the customer, the focal manufacturer confirms the non-standard components' order. Considering the expected delivery date set by the supplier, the focal manufacturer plans the production start for the ETO product.

Model agents' description and modelling methods

The objective of the simulation model consists in capturing the most relevant features of the MTO and ETO supply chains, considering different levels of data aggregation for the model functions.

Manufacturer

As the core manager of the supply chain, the manufacturer's behaviour is driven by management and control functions that allow the flow of physical components and information throughout the supply chain. When the manufacturer receives a new order, it first identifies the type of order, as represented in Figure 2, through the *identifyOrderType* function. Different functions will subsequently be executed, depending on the type of the identified order. When the order type is identified, a new ETO or MTO order agent is created.

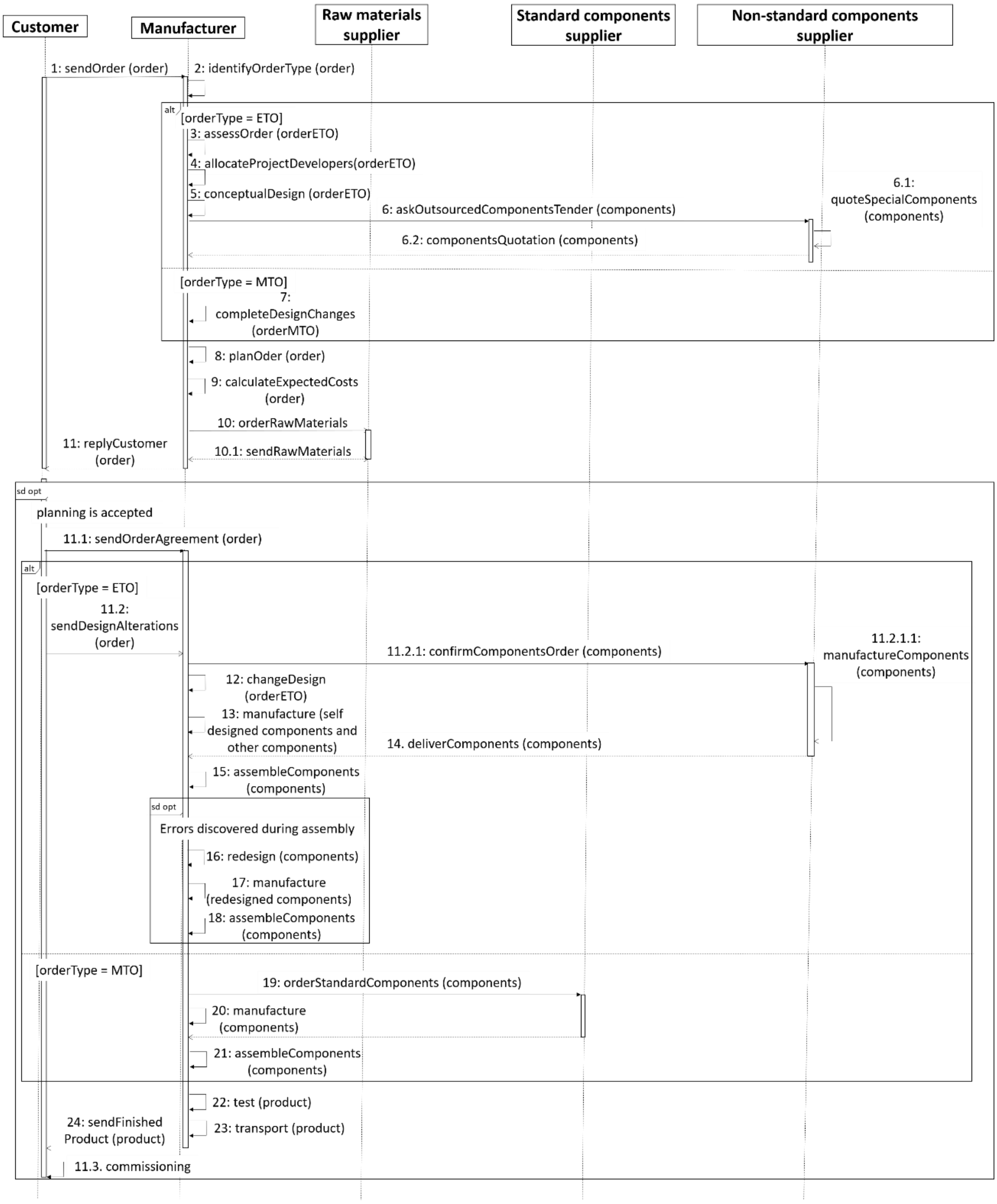


Figure 2. Sequence diagram for the interactions established in the extended hybrid simulation model.

ETO order. The internal behaviour of the ETO order, similarly to the model in Barbosa and Azevedo (2018), is given by a SD model, inspired in the model by Rodrigues et al. (2006), and is represented in Figure 3. Given the temporariness and uniqueness of ETO products, each ETO order was treated as a project (Yang, 2013). SD was the selected modelling method for the project development activities given its strengths in capturing the dynamic behaviour of project execution and the interactions among project variables (Rodrigues, 1994).

After the ETO order agent has been created and following the sequence of activities in Figure 2, the ETO order is assessed, through the *assessOrder* function. During the order assessment stage, the ETO order determinants identified in section 2 are established – project complexity, type, workload, outsourcing, design reuse, and experience/knowledge of the technology. The values of the variables in the SD model, and manufacturing variables are determined during this stage. The conceptual design is also achieved during the order quotation. For this and considering the workload and the date in which the supplier must provide a reply to the customer, the project developers are allocated to the project by the *allocateProjectDevelopers* function. This function considers non-absent project developers for the allocation to the engineering tasks. Also, project developers are preferentially attributed to projects they already have experience in. After the allocation of the project developers, the conceptual design starts by the execution of the SD model. If there are outsourced components in the ETO order, the manufacturer asks for a special components' quotation to the non-standard components supplier. When the non-standard components supplier replies to the components quotation request and the manufacturer finishes the conceptual design, the ETO order specific activities are finished.

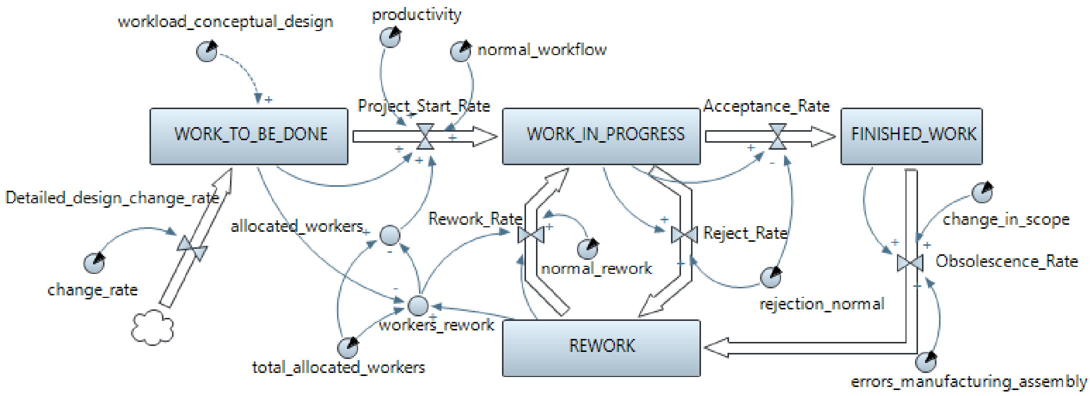


Figure 3. ETO order project development model.

MTO order. MTO orders are simpler than ETO orders. For these, only small alterations are considered. The components, their processing times and routing in the shop floor are known.

Project developers. Project developers are the agents responsible for the project execution and fulfilment of the engineering tasks. These agents' productivity will interfere in the completion of the engineering tasks. New developers have lower productivity than experienced developers. Also, experienced developers may engage in training tasks when there are new developers to train. During these periods of absence, the influence of the developers is not considered for the project. New developers become experienced at a certain rate, and all project developers can quit from job. These agents can be absent for unknown periods of time.

Plan order. After the specific activities for MTO and ETO orders, common activities occur. Planning the orders considers the capacity available at the manufacturer and is operated on a weekly basis. It considers the week hours available in machines at the shop floor, and the number of shop floor employees. For planning purposes, the manufacturer starts by scheduling the activities backward, starting from the delivery date desired by the customer. If a backward planning is not possible due to capacity constraints, a forward planning is made, and the manufacturer proposes a new order delivery date. The lead time for standard or special components is considered by the planning function. Upon planning, if the manufacturer realizes that the shop floor employees are the limiting production resource, temporary employee hiring is scheduled for the needed weeks. This represents an added cost for the orders.

Calculate costs. Considering the resources involved in the order fulfilment, the time spent in the customization/development activities, and the components needed for the product, the expected order costs are calculated.

Order raw materials. Raw materials are ordered on a weekly basis. The amount of raw materials to be ordered was calculated considering the existing raw materials, and the expected needs for the following week. A MOQ must be considered upon ordering. The raw materials are not ordered after a product order has been received. For this, the *orderRawMaterials* function is represented as an asynchronous message in the sequence diagram represented in Figure 2.

Reply to order quotation request. When the manufacturer has finished calculating the order costs, it sends a message to the customer with a prediction of costs and the order delivery date. When the customer accepts the order, the manufacturer engages in further engineering activities, components order, manufacturing, assembly, product testing, and commissioning.

Engineering design alterations and confirmation of special components order. When a customer accepts the manufacturer proposal for an ETO order, it may request engineering design alterations, which are reflected in new components to design – Figure 3, variable *change_rate*, or previously designed components alterations – Figure 3, variable *change_in_scope*. Also, when the customer order is confirmed and there are components in outsourcing, the manufacturer confirms the order of the special components. While the new components are being designed, approved components manufacturing starts when the scheduled date occurs. Re-planning allows re-scheduling the assembly to when all components are expected to be manufactured.

Order standard components. For MTO orders, when the ordered product needs standard components, the manufacturer orders the components from the standard components supplier.

Manufacturing and assembly operations. The shop floor operations of manufacturing and assembly are simulated using DES modelling method, as in (Barbosa and Azevedo 2018). Routing the individual components through the shop floor is considered by the DES model and, for MTO orders, processing times in different machines are known. For ETO orders, and to consider the variability that can be verified, routing and processing times of the components internally produced are randomly selected from combinations available. A high variability for the processing time in the ETO case is considered.

Assembly time is known for MTO products. In ETO products, the assembly time is a function of the complexity level, established during the initial order assessment. In ETO products, during the assembly operations, errors in the integration of the components can be detected. These errors require the re-design of the components and are reflected in the variable *errors_manufacturing_assembly* in Figure 3. The redesigned components must be re-manufactured and finally integrated in the assembly.

Testing, transport, and commissioning. The testing, transport and commissioning activities were also simulated using DES. Product testing occurs at the manufacturer's facility and ensures that the product was correctly assembled and is working. The product is then transported to the customer location, where it will be commissioned.

The manufacturer agent structure is the most complex among the simulated agents. Its modelling objects are summarized in Figure 4.

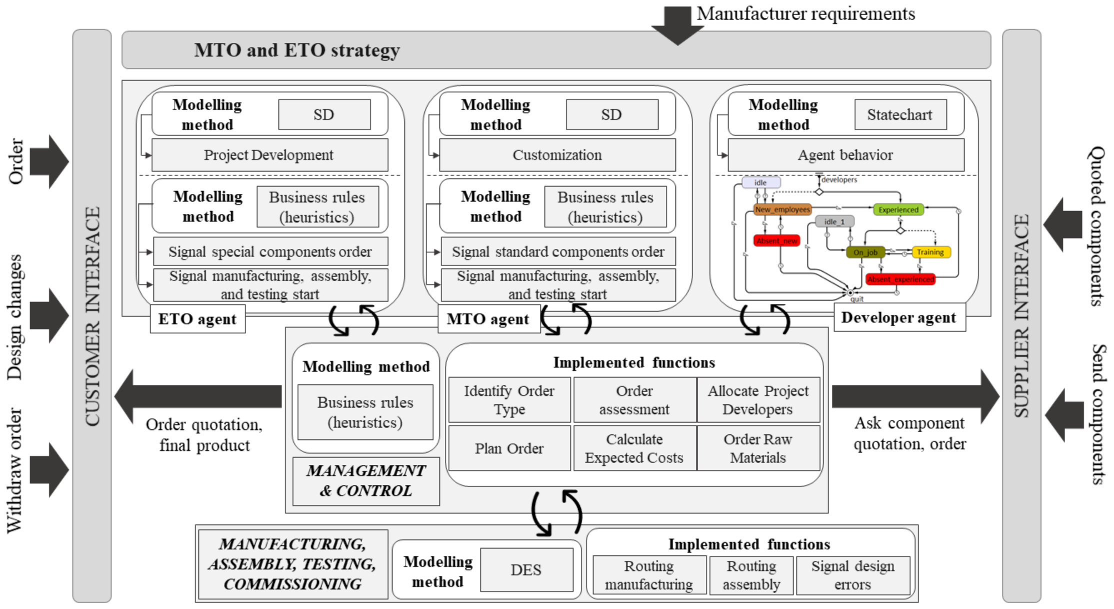


Figure 4. Manufacturer model objects, internal functions, and modelling methods.

Supplier

There are three types of suppliers: raw materials, standard components, and non-standard components. Upon ordering raw materials, whose lead time is known, a MOQ must be respected. For standard components, lead time is also known, but there is no MOQ. These standard components only are ordered when a MTO order has been confirmed. The non-standard components suppliers are responsible for supplying the components that are outsourced in ETO orders. Lead time is unknown *a-priori*, and upon a request for component quotation, the supplier gives an expected cost and lead time.

The manufacturing of the supplied materials is given by a delay in a DES model. This applies to all types of suppliers. Yet, for the non-standard components supplier type, there is an internal function that is used for the components quotation. This function, considering the complexity of the components in outsourcing, will provide an estimate of the cost and the lead time.

Customer

In the proposed model, each customer is an agent, whose behaviour is state-chart defined. As each customer is an individual, its behaviour can change according to the interactions that are established with the manufacturer. It starts by asking an order quotation to the manufacturer. Afterwards, the customer waits for a reply. While waiting for a reply to the tendering request, the customer can withdraw the tendering request when the manufacturer does not provide a response in the adequate time. This represents added costs for the manufacturer that already has started design and planning activities for an order that has been withdrawn.

When the customer receives a reply from the manufacturer, it will assess the manufacturer proposal. If the manufacturer expected delivery time is adequate, the customer will accept the manufacturer proposal. Otherwise, it will withdraw the order. Also, upon assessing the manufacturer proposal, when the order is for an ETO product, the supplier may request alterations to the conceptual design or ask for new components to be designed. It is expected that more alterations will be asked by the customer when the manufacturer is least experienced in a certain product technology. The request for alterations to the design by the customer can occur more than once. The final status of the customer is when it receives the commissioning team and the product is installed at the customer location.

Influence of order determinants in the hybrid simulation model

The performance determinants identified in section 2 will influence the model, particularly for the ETO order execution and progression. To allow the different determinants to have an individual influence in the model, we have associated each performance determinant to one or more model variables, related to an ETO project, or a MTO product. Different levels were defined for each determinant. Upon the order assessment stage, each ETO order is associated to a determinant/model variable level, that will influence the execution of tasks. The identified determinants and the model variables that these influence are presented in Table 2.

Application case and model sampling

Model implementation – the case study

The case study company is an advanced Portuguese labour-intensive metalworking company operating internationally and developing tailored solutions for industrial automation and mechanical engineering. The core products offered by the company include customized industrial conveyors for the food and chemical industries, robotic arms and palletizers. It provides integrated solutions to customers, tailored to individual needs. It produces and sells a wide range of complex, long life cycle products, in low volume. The company is currently employing two manufacturing strategies: MTO and ETO. For standard products, for which small alterations are allowed based on the customers' preferences, the company employs the MTO strategy; for products designed to unique customer requirements, the case company uses an ETO strategy, starting a new product development project for each new order.

Table 2. Performance determinants, model variables affected, and determinant description

	Workload	**Project type**	**Design reuse**	**Outsourcing**	**Complexity**	**Knowledge/experience with technology**
Model variables affected	Workload conceptual design (SD model in Figure 3)	Normal workflow (SD model in Figure 3)	Component reuse; workload conceptual design	Components in outsourcing, workload conceptual design	Rejection normal (SD model in Figure 3), errors in design detected during assembly, assembly time, outsourced components complexity lead time, and cost	Normal workflow deviation, change in scope, change rate (SD model in Figure 3), deviation in expected assembly time
Determinant description	Workload for customization tasks; number of design objects to be considered	Number of product families that will be integrated in the project	Percentage of sub-systems components whose design will be reused and don't have to be designed from scratch	Percentage of components in outsourcing	Expected integration challenges, product operationalization, rework, tasks relative difficulty	Familiarity with the technology being used for the product; it will be reflected in the deviation of the rate at which development tasks progress, and the deviation in the expected assembly operations execution time

It operates in a single facility, in a process layout and using general purpose equipment. On the upstream side of the supply chain, the focal company interacts directly with diverse suppliers – raw materials suppliers, standard components suppliers, and non-standard components suppliers. When demand exceeds the company's manufacturing capacity, specialized labour force is subcontracted for short periods of time (few weeks). Aside from the product development, from the manufacturer's perspective, the assembly stage is the most critical, the longest process and with higher variability. On the downstream side of the supply chain, the manufacturer interacts with the customer, that usually is another business unit.

Orders are dispatched directly from the focal company's facility to the final customer's site; the commissioning team delivers the equipment to the final customers' facility, assembles and validates the equipment operation.

Considering the variability in the projects handled by the case study company, it wishes to assess the impact that projects of different nature will have in its operations and supply chain interactions.

Model sampling and results assessment

The developed model considers that when a new project enters the company system, different determinants are associated to that project. For the MTO projects, only workload is relevant, as the products are well known and minor alterations to the product can be made to accommodate customer requirements. However, for ETO projects, combinations of six different performance determinants are possible. Hence, it is necessary generating random numbers for the performance determinants in each model run for estimating the relevant performance measures, which is achieved using Monte Carlo sampling.

Figure 5 shows the model assessment diagram used in this work. First, a Monte Carlo random sampling is used to achieve different combinations of the performance determinants. The sampling considers the determinants levels established, and the probability distributions for each determinant. At this stage we considered that the different determinants levels distributions followed a uniform discrete distribution, meaning that all levels had equal probability of occurring (Damodaran 2007). The combinations of the determinants were input to the hybrid simulation model, that considered as resources the project developers, the machines, and the shop floor employees, with side support functions that allowed identifying the order type and planning the order. The measures retrieved from the simulations include the project time – duration of development project, including design revisions -, the manufacturing and assembly time, including re-manufacturing of components, and the total project cost. The hybrid simulation output is used to assess the system performance variability, through the histograms of the performance measures. Central tendency measures characterizing the data were retrieved and, for nonlinear data, non-parametric Spearman correlation was used to measure the statistical association among the random variables (Firestone et al. 1997). Finally, the extreme situations associated to the output measures were analysed to understand the determinants levels more often associated to data outliers, which are the most critical. This was made by obtaining the Pareto charts for the outliers.

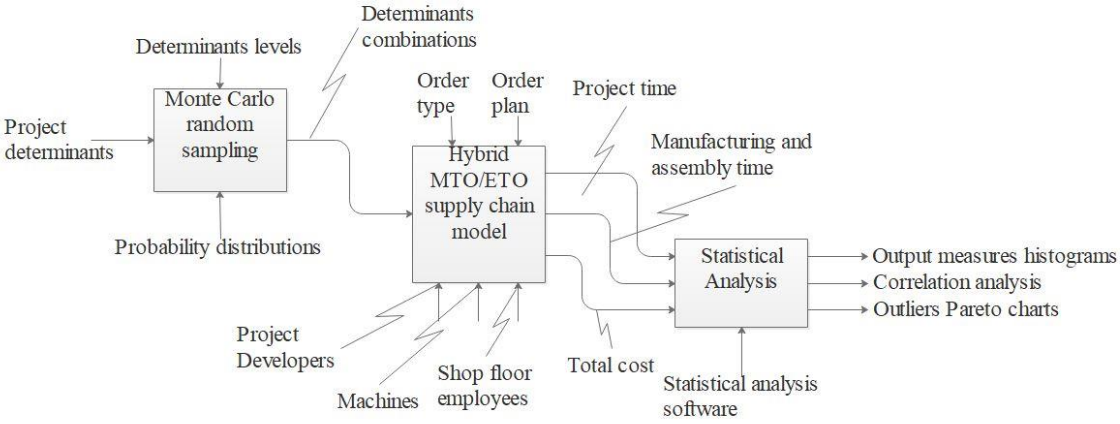


Figure 5. Diagram of the model assessment.

Model instances

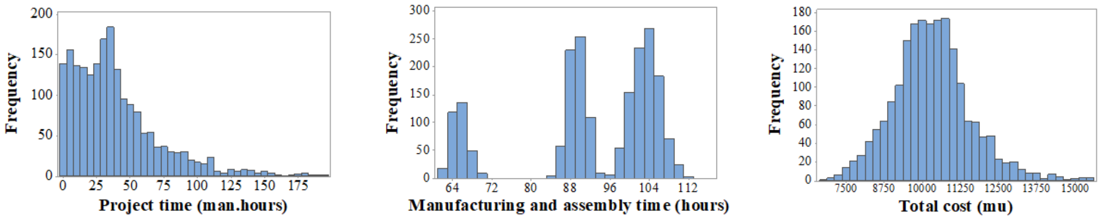
Considering the case study company, for the MTO products, a total of six product families have been considered. For MTO products, only the workload determinant will be considered. A uniform discrete distribution, varying between zero (no need to alter product components) and 20 has been considered for the workload. This probability distribution has been selected to attribute randomness to the number of components to be customized in a MTO order, but without a clearly defined tendency – there is an equal probability of occurrence of the number of components to be customized, within the established limits. For each product family, and following previous publications (Das et al. 2012; Deliktas, Torkul, and Ustun 2017), the manufacturing and assembly times followed a normal distribution, known upfront. Product families requiring ordered components were known. Table 4 in the appendices presents the manufacturing and assembly input data for the considered product families.

For the ETO projects we considered five possible routing scenarios in the case company shop floor and highly variable manufacturing times. Each determinant identified in Table 2 has different levels, and for each level are defined variation ranges for the affected model variables, as presented in Table 5 in the appendices.

Results and discussion

To assess the outputs from the Monte Carlo simulation, the histograms and basic statistics of the output performance measures project time, manufacturing and assembly time, and project cost were obtained for MTO and ETO projects, and are presented, respectively, in Figure 6 and Figure 7. The number of samples considered in the Monte Carlo simulation was 2 000, which ran in 4500 seconds, in an Intel® Core™ i5-6200U CPU 2.40GHz. The number of model replications for the Monte Carlo simulation has been determined by the confidence interval method (Robinson 2004), for a 90% confidence interval. The Anylogic software was used to implement the simulation model, and Minitab was used for retrieving the statistics from the simulation.

In Figure 6(a), the results obtained for the distribution of the MTO project time, measured in man.hours, show a histogram that is right skewed. The mean value obtained was 38,78 man.hours, with a standard deviation of 32,88 man.hours. Despite these being the common central tendency measures more often used, the histogram data does not show a symmetrical distribution, as confirmed by the skewness value in the table. For skewed distributions, other central tendency measures should be used. The median value of 32,00 man.hours is more representative of centre of the data, and the Interquartile range (IQR) of 37,00 man.hours is a better measure of the data spread than the standard deviation. Upon investigating the causes of the higher project times, associated to the histogram tail, it is concluded that the workload plays a relevant role, with the higher project development times being associated to workload values higher than 12 parts. A correlation analysis revealed a statistically significant linear relationship (p-value<0,001, which is lower than the significance level of 0,05, and R-squared value of 52,89%) between the project time and the workload, with a positive correlation (r=0,73) indicating that an increase in the workload tends to increase the project time.



Number of samples	2000
Mean	38,78
Standard error of the mean	0,735
Trimmed mean	35,65
Standard deviation	32,88
Coefficient of variation	84,79
Median	32,00
IQR	37,00
Skewness	1,51

(a)

Number of samples	2000
Mean	92,39
Standard error of the mean	0,31
Trimmed mean	93,10
Standard deviation	13,79
Coefficient of variation	14,92
Median	94,16
IQR	15,34
Skewness	-0,96

(b)

Number of samples	2000
Mean	10314,00
Standard error of the mean	28,40
Trimmed mean	10280,00
Standard deviation	1271,00
Coefficient of variation	12,32
Median	10263,00
IQR	1479,00
Skewness	0,48

(c)

Figure 6. Histograms and basic statistics that result from the Monte Carlo simulation when MTO orders are considered. (a) Project time; (b) Manufacturing and assembly time; (c) Total cost.

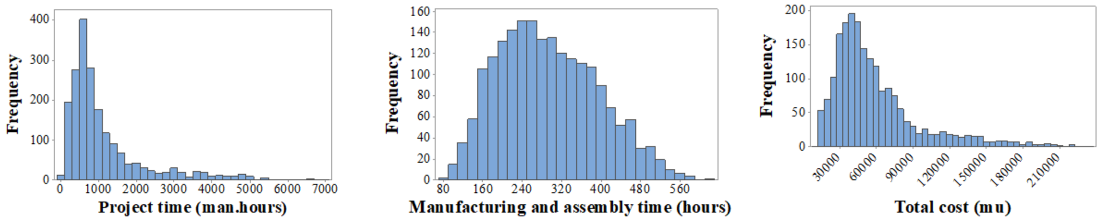
The histogram of the ETO project time, represented in Figure 7(a), shows a mean value of 1185,2 man.hours, with a standard error of the mean of 25,6 man.hours, and a standard deviation of 1143,5 man.hours. The median is 765,0 man.hours and the trimmed mean is 1041,8 man.hours. This value is smaller than the mean, because it is obtained ignoring 5% of the highest and 5% of the lowest values recorded. This eliminates some outliers and the influence of the tail values. The coefficient of variation for the project time is 96,49.

The Spearman correlation results in Table 3 for the project time show a p-value that is lower than the significance level of 0,05, showing evidence of the association between the performance determinants and the project time. The Spearman rho correlation coefficients are positive for the workload, project type, and complexity, showing a positive relationship between these determinants and the project time, which means that as these determinants increase in level, there is a tendency for the project time to increase; the correlation coefficients are negative for the design reuse, outsourcing, and knowledge/experience with technology determinants, which indicates that as these determinants increase in level, there is a tendency for the decrease in the project time. The largest absolute value of the Spearman coefficient was obtained for the workload determinant, showing a stronger relationship with the project time.

Despite both histograms in Figure 6(a) and Figure 7(a) presenting a positively skewed distribution, the median value of the project time for the ETO projects is approximately 23 times higher than in MTO projects. This is in line with the literature, that states the long project times associated to the new products that are developed upon customer specifications.

The distribution of the manufacturing and assembly time, measured in hours, in Figure 6(b), shows three peaks, associated to the different assembly times of the MTO products, and presented in Table 4 of the appendices. The workload shows no correlation with the manufacturing and assembly time. Indeed, regardless the number of components that must be altered in each MTO project, the same number of components is produced and assembled for the same product. A histogram for the manufacturing and assembly time of the ETO projects, measured in hours, is presented in Figure 7(b). The histogram shows slightly positive skewed data (skewness value of 0,36), with a mean of 293,3 hours, a standard error of the mean of 2,26 hours, and a standard deviation of 100,97 hours. The trimmed mean and the median values do not vary much from the mean, despite the slight data skewness. The

MTO assembly and manufacturing times show significantly lower values when compared to ETO projects.



Number of samples	2000
Mean	1185,20
Standard error of the mean	25,60
Trimmed mean	1041,80
Standard deviation	1143,50
Coefficient of variation	96,49
Median	765,00
IQR	863,50
Skewness	2,07

(a)

Number of samples	2000
Mean	293,30
Standard error of the mean	2,26
Trimmed mean	290,66
Standard deviation	100,97
Coefficient of variation	34,42
Median	284,64
IQR	153,27
Skewness	0,36

(b)

Number of samples	2000
Mean	59828,00
Standard error of the mean	832,00
Trimmed mean	55955,00
Standard deviation	37226,00
Coefficient of variation	62,22
Median	49021,00
IQR	36011,00
Skewness	1,72

(c)

Figure 7. Histograms and basic statistics that result from the Monte Carlo simulation when ETO orders are considered. (a) Project time; (b) Manufacturing and assembly time; (c) Total cost.

Table 3. Spearman correlation coefficient values between the ETO performance determinants and the ETO projects performance measures

Measures		**Workload**	**Project type**	**Design reuse**	**Outsourcing**	**Complexity**	**Knowledge/experience with technology**
Project time (man.hours)	Spearman rho	0,442	0,414	-0,170	-0,182	0,212	-0,097
	p-value	0,000	0,000	0,000	0,000	0,000	0,000
Manufacturing and assembly time (hours)	Spearman rho	0,878	-0,016	-0,026	-0,284	0,279	-0,063
	p-value	0,000	0,481	0,247	0,000	0,000	0,005
Total cost (mu)	Spearman rho	0,673	0,285	-0,172	-0,047	0,222	-0,112
	p-value	0,000	0,000	0,000	0,042	0,000	0,000

According the results for the correlation between the performance determinants and the manufacturing and assembly time in Table 3, it is possible to infer that there is no evidence of association between the type and design reuse determinants and this performance measure. This is verified by the p-value, that is higher than the significance level of 0,05. This agrees with the data input in the model, as these determinants are not related to model variables at the manufacturing and assembly levels. The workload and complexity determinants show a positive correlation coefficient which indicates that an increase in these determinants levels tends to increase the manufacturing and assembly time. The outsourcing and knowledge/experience with technology determinants show a negative correlation coefficient, indicating that as these determinants level increases, the manufacturing and assembly time tends to decrease.

A mean project cost of 10314,0 monetary units for the MTO projects was obtained, as is presented in Figure 6(c). Despite the slight skewness of the histogram (skewness value of 0,48), the median and trimmed mean values do not differ much from the mean value. There is a significant relationship between the total MTO project costs and the workload (p-value<0,001 and R-squared value of 32,90%). There is a positive correlation (r=0,57) between these, which indicates that when the workload increases, the total costs also tend to increase. Finally, the histogram of the total ETO project cost, is represented in Figure 7(c). As in the project time histogram, the total project cost data is positively skewed, with the mean value being highly affected by the outliers and extreme values represented by the distribution tail. The costs obtained for the ETO projects are much higher than the costs of the MTO products.

As with the project time, the correlation results in Table 3 show there is evidence for the association between all performance determinants and the project total cost. While the increase in the workload, project type, and complexity levels tend to increase the project costs (given the positive correlation coefficient), the level increase for the design reuse, outsourcing, and knowledge/experience with technology tends to decrease the project total costs.

Given the long tails of the histograms for the project time and the total cost for the ETO projects, it is important identifying the presence of outliers in the data. As the box-plots in Figure 8 show, many outliers exist for the project time, Figure 8(a) and total cost measures, Figure 8(c), while for the manufacturing and assembly times, Figure 8(b), only one outlier was obtained.

These outliers should not be ignored and is important understanding under which input determinants levels these occur. To assess this, for the project time and total cost measures, we plotted the Pareto charts for the outliers, as presented in Figure 9.

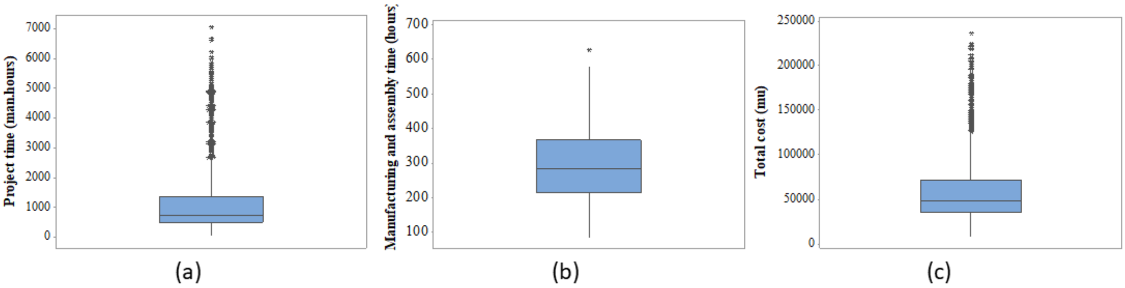
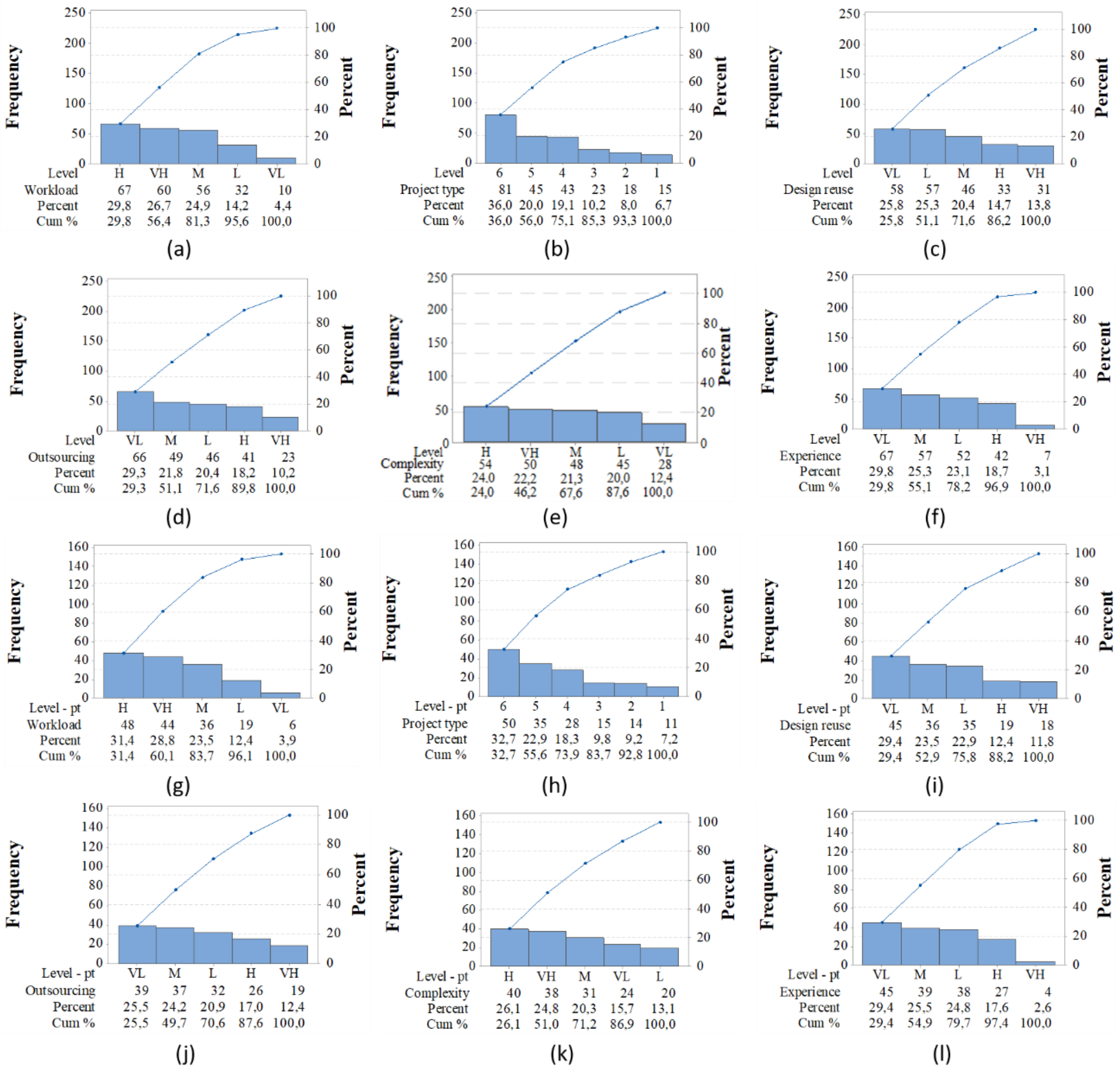


Figure 8. Box plot graphics for the assessed performance measures. (a) Project time; (b) Manufacturing and assembly time; (c) Total cost.

The results obtained for the Pareto charts for the project time show that the outliers occur for higher levels of workload, project type, and complexity, and for lower levels of design reuse, outsourcing, and knowledge/experience with technology. In the project time outliers, for the workload, Figure 9(a), the project type, Figure 9(b), and the complexity, Figure 9(e), levels, around 70% or more of the outliers are verified for the three highest levels in the scale (levels very high(VH), high(h), and medium (M) for the workload and complexity, and levels 6, 5, and 4 for the project type). For the design reuse, Figure 9(c), outsourcing, Figure 9(d), and knowledge/experience with technology, Figure 9(f), over 50% of the outliers occur for the two lowest levels, the very low(VL) and the low(L), or for the VL and M levels. Among all the determinants, the highest percentage of project time outliers is verified for the project type level 6. For the project cost outliers, in Figure 9(g)-(l), similar observations can be withdrawn.

Among the determinants considered, the highest percentage of total cost outliers is registered for the level 6 of the project type. It affects the normal project workflow. Lower workflows (verified for higher project type levels) may be associated to the need of allocating more project developers to a project, increasing the total project costs. Lower workflows also lead to higher time requirements for the project development. Despite these observations, the project type determinant should not be considered in isolation, as the results show that other determinants are relevant and should be considered simultaneously.

The results show that, particularly for ETO products, the performance determinants have great influence in the performance measures. While high levels of workload, project type, and complexity increase the project time and the total costs, lower levels of outsourcing, knowledge/experience with technology, and design reuse, are also associated to increased levels of these performance measures. From a practical perspective, while the proposed hybrid model allows predicting these performance measures, some variability is expected even for projects with similar determinants. A conjoint analysis of the impact of the six performance determinants is important when assessing the projects being accepted by the company.



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l)

Figure 9. Pareto charts for the outliers detected. (a) Workload in Project time; (b) Project type in Project time; (c) Design reuse in Project time; (d) Outsourcing in Project time; (e) Complexity in Project time; (f) Knowledge/experience with technology in Project time; (g) Workload in Total cost; (h) Project type in Total cost; (i) Design reuse in Total cost; (j) Outsourcing in. Total cost; (k) Complexity in Total cost; (l) Knowledge/experience with technology in Total cost.

Conclusions and future research directions

This work's contribution to the literature is twofold. On one hand, a set of MTO/ETO supply chain performance determinants, including complexity, design reuse, workload, project type, outsourcing, and knowledge/experience with technology, are proposed for classifying development projects. On the other hand, a hybrid SD-DES-ABS simulation model for the MTO/ETO supply chain performance assessment is proposed, that considers the impact of the bespoke activity through the performance determinants as model inputs for classifying the projects that a company undertakes. The proposed simulation model integrates relevant supply chain actors, including different types of suppliers, MTO and ETO customers, and a focal manufacturer. The manufacturer undergoes activities of product development, manufacturing, assembly, testing and commissioning, that are supported by side functions, including development resources allocation, order plan, order cost assessment, and ordering of raw materials and components. Given the very different nature of the activities and functions considered, the hybrid simulation approach was considered the most appropriate.

For the case study considered, the workload has a big impact in the project time and total cost of the MTO products, while having zero impact in the manufacturing and assembly time.

This was verified because the manufacturing and assembly activities only are affected by the type of portfolio product being manufactured/assembled, while the number of design objects being adapted to the customer requirements only had impact in the development activities duration, and consequently in the total cost. For the ETO products, all the determinants had impact in the project time, and total costs, while there was no evidence of association of the project type and design reuse determinants with the manufacturing and assembly time.

Despite the proposed approach being valuable for the MTO/ETO supply chain performance assessment, it has only been applied to a case study company, which impedes the generalization of the results obtained. However, given the resemblance of the case study company to the literature referred features for the MTO and ETO companies, the results are still pertinent, and the proposed model structure could be easily applied to other case companies. Furthermore, the levels attributed to the performance determinants and the cost structure impact and biased the results, meaning that other input values for the levels could lead to different results.

Further improvements to this work should be well-thought-out. First, the application of the model to other companies to promote results generalizability. Secondly, the results obtained in this work considered that any combination of determinants was possible, and that all determinants levels had equal probability of occurrence, but this might not be applicable in real situations. For this, assessing the model results considering constraints among the levels of the performance determinants would be a useful study. Though the performance determinants which have been identified in the literature are associated to model variables which have a direct correspondence with the real modelled system variables, future work should include finding a better association between the performance determinants and the variables affected by the determinants, e.g. through questionnaires responded by experts about the system. Also, complementary prediction tools could enhance the obtained results, e.g. the use of machine learning algorithms to predict the impact of the performance determinants in different measures.

Acknowledgements

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Appendices

Table 4. MTO products model input data

Product family	Assembly time average (hours)	Assembly time standard deviation (hours)	Supplier dependencies?
A	28,0	2,5	Yes
B	24,0	1,7	No
C	32,0	2,0	No
D	24,0	1,4	Yes
E	24,0	0,8	No
F	16,0	0,4	No

Table 5. Determinants, levels, and model affected variables

<table>
<tr><th>Determinant</th><th>Levels</th><th colspan="9">Affected variables</th></tr>
<tr><td rowspan="6">Workload</td><td></td><td colspan="4">Workload conceptual design minimum (components)</td><td colspan="5">Workload conceptual design maximum (components)</td></tr>
<tr><td>Very Low</td><td colspan="4">40</td><td colspan="5">80</td></tr>
<tr><td>Low</td><td colspan="4">81</td><td colspan="5">120</td></tr>
<tr><td>Medium</td><td colspan="4">121</td><td colspan="5">160</td></tr>
<tr><td>High</td><td colspan="4">161</td><td colspan="5">200</td></tr>
<tr><td>Very high</td><td colspan="4">201</td><td colspan="5">240</td></tr>
<tr><td rowspan="7">Project type</td><td></td><td colspan="9">Normal workflow (components/time)</td></tr>
<tr><td>1</td><td colspan="9">0,40</td></tr>
<tr><td>2</td><td colspan="9">0,35</td></tr>
<tr><td>3</td><td colspan="9">0,3</td></tr>
<tr><td>4</td><td colspan="9">0,25</td></tr>
<tr><td>5</td><td colspan="9">0,20</td></tr>
<tr><td>6</td><td colspan="9">0,15</td></tr>
<tr><td rowspan="6">Design reuse</td><td></td><td colspan="4">% design reuse minimum</td><td colspan="5">% design reuse maximum</td></tr>
<tr><td>Very Low</td><td colspan="4">0,00</td><td colspan="5">0,10</td></tr>
<tr><td>Low</td><td colspan="4">0,11</td><td colspan="5">0,20</td></tr>
<tr><td>Medium</td><td colspan="4">0,21</td><td colspan="5">0,30</td></tr>
<tr><td>High</td><td colspan="4">0,31</td><td colspan="5">0,4</td></tr>
<tr><td>Very high</td><td colspan="4">0,41</td><td colspan="5">0,5</td></tr>
<tr><td rowspan="6">Outsourcing</td><td></td><td colspan="4">% of outsourcing minimum</td><td colspan="5">% of outsourcing maximum</td></tr>
<tr><td>Very Low</td><td colspan="4">0,00</td><td colspan="5">0,10</td></tr>
<tr><td>Low</td><td colspan="4">0,11</td><td colspan="5">0,20</td></tr>
<tr><td>Medium</td><td colspan="4">0,21</td><td colspan="5">0,30</td></tr>
<tr><td>High</td><td colspan="4">0,31</td><td colspan="5">0,4</td></tr>
<tr><td>Very high</td><td colspan="4">0,41</td><td colspan="5">0,5</td></tr>
<tr><td rowspan="6">Complexity</td><td></td><td colspan="2">Rejection normal minimum (components/time)</td><td colspan="4">Rejection normal maximum (components/time)</td><td colspan="2">Probability of errors in manufacturing detected during assembly</td><td>Assembly time (minutes)</td></tr>
<tr><td>Very Low</td><td colspan="2">0,000</td><td colspan="4">0,02</td><td colspan="2">0,01</td><td>2400</td></tr>
<tr><td>Low</td><td colspan="2">0,021</td><td colspan="4">0,04</td><td colspan="2">0,03</td><td>3840</td></tr>
<tr><td>Medium</td><td colspan="2">0,041</td><td colspan="4">0,06</td><td colspan="2">0,05</td><td>4800</td></tr>
<tr><td>High</td><td colspan="2">0,061</td><td colspan="4">0,08</td><td colspan="2">0,07</td><td>5760</td></tr>
<tr><td>Very high</td><td colspan="2">0,081</td><td colspan="4">0,10</td><td colspan="2">0,09</td><td>6720</td></tr>
<tr><td rowspan="6">Knowledge/ experience with technology</td><td></td><td>Deviation to normal workflow (components/ time)</td><td colspan="2">Change rate maximum (components/ time)</td><td colspan="2">Change rate minimum (components/ time)</td><td colspan="2">Change in scope maximum (components/ time)</td><td>Change in scope minimum (components/ time)</td><td>Deviation in assembly time (minutes)</td></tr>
<tr><td>Very Low</td><td>0,05</td><td colspan="2">0,02</td><td colspan="2">0,17</td><td colspan="2">0,2</td><td>0,17</td><td>250</td></tr>
<tr><td>Low</td><td>0,04</td><td colspan="2">0,16</td><td colspan="2">0,13</td><td colspan="2">0,16</td><td>0,13</td><td>200</td></tr>
<tr><td>Medium</td><td>0,03</td><td colspan="2">0,12</td><td colspan="2">0,09</td><td colspan="2">0,12</td><td>0,09</td><td>150</td></tr>
<tr><td>High</td><td>0,02</td><td colspan="2">0,08</td><td colspan="2">0,05</td><td colspan="2">0,08</td><td>0,05</td><td>100</td></tr>
<tr><td>Very high</td><td>0,01</td><td colspan="2">0,04</td><td colspan="2">0,01</td><td colspan="2">0,04</td><td>0,01</td><td>50</td></tr>
</table>

Paper F

Towards a supply chain sustainability conceptual model for performance assessment: a case in the commercial aircraft industry

Cátia Barbosa, Américo Azevedo, Carlos Malarranha, Ana Carvalho, Ana Barbosa-Póvoa

Paper presented at the 5th International EurOMA Sustainable Operations and Supply Chains Forum,
Kassel, Germany

Abstract - Commercial airplane manufacturers are nowadays pushed to compete through more efficient supply chains and to develop more efficient aircrafts in order to reduce emissions and airplane fuel costs. This enhances the relevance of new product development activities through advanced materials, and production processes. Hence, we intend to assess the sustainability performance in the aerospace industry supply chain during the adoption of advanced materials and production processes, using a simulation approach. Using a real case study, we explore the impact of the introduction of four materials/manufacturing processes in the aerospace supply chain sustainability performance. Results regarding CO_2 emissions, energy use, supply chain costs, and workload levels are assessed.

Keywords - Aerospace supply chain sustainability, Hybrid simulation, New product development

Introduction

Different factors have been pushing aircraft manufacturers to produce more efficient airplanes with more efficient supply chains (SCs). On one hand, airlines wish to reduce fuel costs, responsible for 30% of the total airplanes' operating costs; and on the other hand, with 2% of global CO_2 emissions resulting from air transport worldwide, governments and society have been demanding more sustainable aircrafts and SCs (IATA, 2013). For this, original equipment manufacturers (OEMs) have undergone significant new product development (NPD) efforts by reducing the airplanes' weight using advanced materials in the aero structures, and improving the engines' efficiency (Tang et al., 2009). Challenges in this context have been demanding for the aerospace SC, with considerable unwanted cost of delays and increased time-to-first airplane unit (Tang et al., 2009).

As some airplanes introduction programs failed to achieve the desired performance levels, industry players embraced new approaches to the NPD process. The objectives of these development programs are twofold: first, reducing product development cycles, and second, improving sustainability oriented performance (Airbus, 2016). As many sustainability concerns have been emerging in the aerospace SC, in this work we respond to the following research question: What is the impact in sustainability performance of introducing new materials/technologies in the aerospace SC? This work aims to develop a conceptual model for assessing SC sustainability performance during NPD in the aerospace industry, focusing on the introduction of advanced materials and production processes.

An approach for SC sustainability performance assessment is developed using simulation model, to assess relevant sustainability metrics in the aerospace industry. Using this approach, it is possible to identify performance variations induced by using different combinations of materials and manufacturing processes – scenario analysis. The different SC actors are modelled as individual agents, whose locations are real; transportation is also modelled as agents, whose behaviour is defined by a statechart, allowing tracking the differences in costs and environmental impact from using different transportation modes. Furthermore, discrete event simulation (DES) is used for simulating the transport of materials and products between the SC actors and the generic process delay from obtaining the materials at the supplier level. Finally, System Dynamics (SD) and business rules are explored to represent the manufacturer behaviour through a policy structure of inventory, and manufacturing.

Countless metrics can be used for assessing the SC sustainability impact of using different materials/processes. In this work, and following a triple bottom line approach (3BL), the following metrics were considered: CO_2 emissions, energy consumption, global SC costs, segmented SC costs – transport, materials, process, workforce -, and workload, measured as the total worker direct working hours.

The remaining of the paper is organized as follows: first a state of the art is presented, followed by the detailed explanation of the proposed simulation model. The case study and the instances used in the model implementation are presented, followed by the results and discussion. The paper ends with the conclusions and future research.

State of the art

Unlike in other industries, sustainability in aerospace SCs has not been much explored by academia. Based on existing literature and in a case study of British Aerospace (BAe) Systems, Gopalakrishnan et al. (2012) analysed the sustainability drivers and developed two conceptual models that evidence the interdependence of 3BL and the relevant elements required for a sustainable SC. In a related research, Ruiz-Benitez et al. (2017), studied the environmental advantages of lean, green and resilient SC management, in a case of aerospace sector. Also, Romaniw and Bras (2012), focused in manufacturing, developing a survey for the understanding of the common practices in sustainable aerospace manufacturing for helping future research.

Hybrid simulation approaches have been successfully used in the literature for the evaluation of the effects of alternative policies and improvement initiatives in performance. In Akkermans (2001), the author applied SD enriched with agent-based principles to the simulation of decentralized supply networks in the case of a lithographic equipment manufacturer. Schieritz and Größler (2003) proposed the use of an overall simulation environment using agents, whose internal decision structures were modelled using SD. In Schieritz and Milling (2003) the authors used the same principles of integration between agent based simulation (ABS) and SD, and proposed a generic agent structure, including a data interface module for materials and information exchange, a scheduling module, an ordering module for setting the orders levels according to the agents' needs and a supplier evaluation module for establishing preferential connections with suppliers, considering their past performance.

In Umeda and Zhang (2010), the authors proposed a SC system network, including six types of agents: supplier, source, storage, consumer, deliverer, and manager. Each member was an agent, whose actions were performed according to pre-defined mechanisms. SD models were used for describing the consumers reaction and feedback to a given SC performance.

Jain et al. (2013) developed a hierarchical hybrid SD-DES-ABS model for estimating the energy consumption for maintaining the products flowing through a SC. The SD model was used for analyzing the SC in high level decisions, as alternative SC configurations. The alternatives from the SD model were studied for settling the SC design and operational policies. For the links of the SC for which opportunities for improvement were identified, discrete event models were developed. Agent-based models were used for exploring trade-offs in situations in which many people were involved. In Abduaziz et al. (2015), the authors proposed a hybrid SD-DES model for assessing green logistics practices in the automotive industry. Four sub-models, for energy consumption, waste, water and CO_2, were created using the SD method. From the SD model, opportunities for improvement were identified. For those improvement opportunities, detailed discrete event models of the operational processes were designed and implemented. The results of the discrete event models were given as input to the SD sub-models to improve results.

As referred by Jain et al. (2013), using simulation modelling for assessing sustainability when compared to more conventional methods (e.g. conventional LCA methods), brings the advantage of considering time and the dynamic behaviour of the SC. Despite the value that simulation can have in the aerospace industry (Tannock et al., 2007), few simulation studies in this industry can be identified. Unlike the existing literature, the proposed simulation model not only assesses an emerging industrial trend, but also focuses on the sustainability of the aerospace SC, a problem not yet commonly addressed per se, nor through simulation methods.

Simulation model

We propose a hybrid model that builds on the analysis of the SC considering agents as the model building blocks. This idea was proposed in Schieritz and Größler (2003), where SC participants were modeled as agents, whose internal behaviour was represented in SD. Unlike in the approach from Schieritz and Größler (2003), in the proposed approach, not only SD is used for defining the internal behaviour of the SC agents, but also business rules and DES. The developed SC model focuses on the perspective of a major aerospace parts supplier, serving directly the OEM; yet we also consider in the model, the action of the suppliers, the OEM, and the airports and seaports where material and product transfer between transportation modes occur. Each SC member is positioned in a Geographic Information System (GIS) map, from which relevant information, as the distance between agents, is retrieved. The overall SC simulation model is presented in Figure 1.

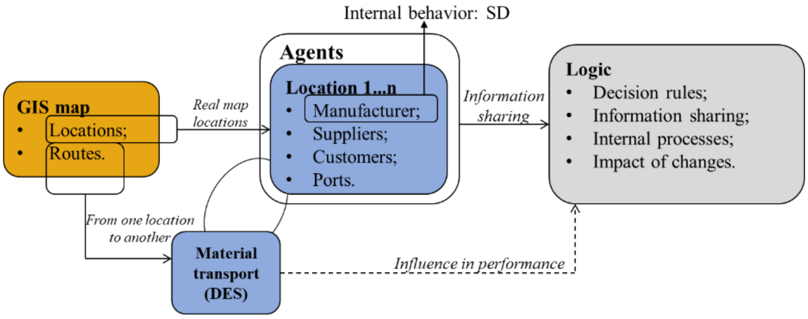


Figure 1 – Hybrid SC simulation model.

Customer agent – the OEM

The customer agent is the demand driver in the model. Considering information gathered from aerospace industry experts during workshops, three demand periods are considered – fixed, promised, and forecasted. The first, fixed demand is a demand period for fixed orders, that will not be subject to alterations; the second demand period, promised is a subsequent demand period that will be used by the manufacturer for planning purposes, but that can still be subject to changes; finally, forecasted demand is a very broad perspective of the demand level for more distant periods of time. In the implemented model, the fixed, promised, and forecasted demand values are updated by the customer every six months.

Manufacturer agent

As previously referred, the internal behaviour of the manufacturer agent will be given by a SD model and business rules. The SD model is based on a model proposed by Sterman (2000), for the policy structure of inventory and production. Alterations to the original model were made as deemed necessary. The model structure is presented in Figure 2.

Furthermore, business rules are used for establishing the time of ordering materials from suppliers. A description for the implemented business rule is as follows:

```
Calculate required materials for fixed period;
If Materials Stock > required materials
     No need to order for fixed period;
Else
     Order missing materials for current period;
Calculate required materials for promised period;
Schedule an event to order materials for the promised period.
```

The manufacturer agent also has internally defined the transport of the final product to the OEM, given by a DES model.

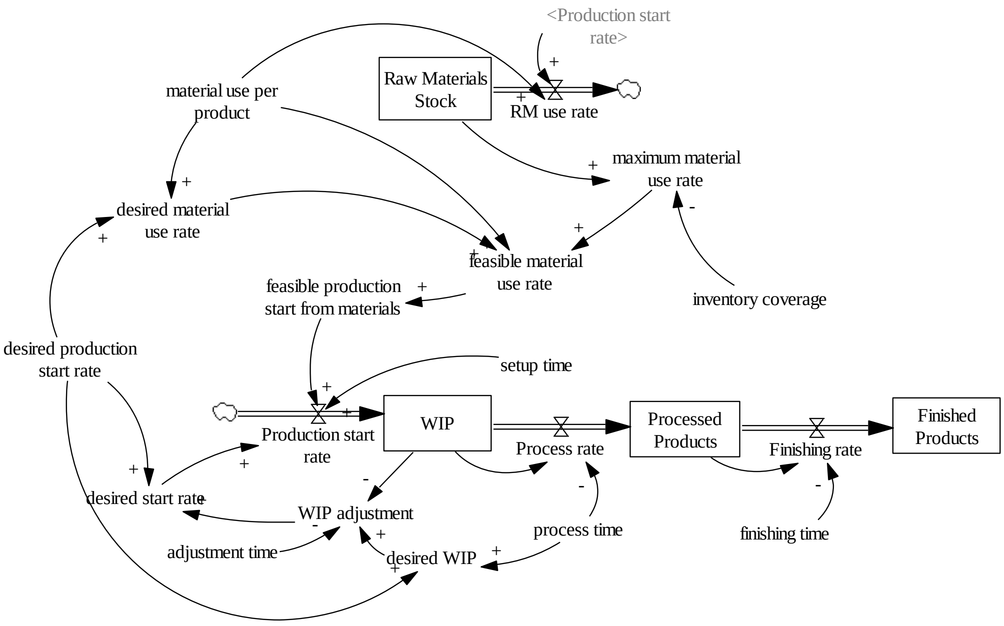


Figure 2. SD behaviour model for the manufacturer agent.

Supplier agent

The supplier agents receive orders from the manufacturer. When the supplier agent receives an order, it will determine whether the order can be fulfilled in a single delivery or if more deliveries will be necessary. This is determined by the transport capacity of the trucks. After this assessment, the supplier starts processing the materials ordered. The processing of the materials is represented by a simple delay (according to expected supplier lead time values), in DES model. As in the manufacturer, the supplier agent has the transport function represented by a DES model.

Material transfer points – airports and seaports

In the proposed model, when the agents between whom materials and final products are exchanged are in different continents, different transport modes are used. The transfer of materials and final products between modes occurs at seaports and airports. The internal behaviour of these agents is given by a DES model that determines if the materials/final products are being transferred from a truck to a ship or an airplane, or from an airplane or a ship to a truck.

Transportation resources – trucks, airplanes, and ships

Each transportation resource is modelled as an agent. These exist in limited number inside the supplier, manufacturer, seaports, and airports agents. The vehicles receive information from their owners to transport materials and final products. Their action is represented by five internally defined states: at owner, loading materials/final products, going to specified location, unloading materials/final products, and returning to owner. Each vehicle used has an associated monetary cost and environmental impact.

Case study

Description of the case study

This simulation work is based on a case study of an aerospace manufacturer that produces critical aero structures in carbon-fiber composites, through the autoclave curing process. The company supplies directly the OEM and operates as tier 1 and tier 2. The manufacturer and OEM engineering centres are in a process of collabourative development with scientific institutes to introduce new out-of-autoclave (OoA) products and processes exploring the use of composite materials.

In this context four manufacturing processes are studied: one bag molding that is cured in autoclave, and three that are cured OoA, such as vacuum assisted resin injection (VARI), vacuum-bag-only (VBO) and thermo-stamp processes. The bag molding is an open-mold process. This manufacturing method results in toxic emissions arising from the resin, leading to environmental pollution. Closed molding processes like VARI and VBO offer improvements in environment and in other areas like productivity, quality, and in social questions as the employee retention (Schwartz, 2011). The materials used in the first three processes are thermoset materials, not being easily recycled (Liu et al., 2018). In addition, the bag molding and VBO processes use prepregs materials, needing a cold-chain logistics and a temperature-controlled room storage. The thermo-stamp process uses thermoplastic-type prepregs composites. This process has shorter manufacturing cycles, and the material can be stored at ambient temperature allowing significant reductions in energy costs. Thermoplastic materials are also 100 per cent recycled and valued (Airbus, 2015). Table 1 summarizes the considered processes.

Table 1. Composite manufacturing processes considered in the context of this work

Curing technology	**Autoclave**	**Out-of-Autoclave**	**Out-of-Autoclave**	**Out-of-Autoclave**
Matrix type	Thermoset	Thermoset	Thermoset	Thermoplastics
Product form	Prepreg	Fibers and resin	Prepreg	Prepreg
Manufacturing process	Bag molding	VARI	VBO	Thermo-stamp
Environmental	Some pollution	Low pollution	Low pollution	Low pollution
Recycling	Difficult	Difficult	Difficult	100%
Transport	Cold-chain logistics	Common logistics	Cold-chain logistics	Common logistics

The various options available in terms of OoA materials and technologies have hampered the development process, given the various decision variables involved, particularly in terms of the impact on SC sustainability performance. VBO, VARI, and thermos-stamp OoA processes are being considered. The process currently in production and the three processes under development will be studied in the form of scenarios, each process corresponding to a scenario. The materials are supplied to the manufacturer through locations scattered all over the planet and transported by truck and airplane. The manufacturer in turn ships to the OEM via truck and ships.

Model implementation and model instances

Considering its multi-method modelling possibility, the Anylogic platform was selected for the model implementation. To ensure that the model provides accurate information, it was verified through debugging; for validation purposes, and following techniques specified by Sargent (2011), the model was subject to extreme conditions testing, internal validity testing, and parameter variability.

The model instances used in this work for the different scenarios considered were those specified in Table 2. Values used for the assessment of the environmental performance of the transportation activity, considered values of emissions available in SimaPro Ecoinvent version 8.2.3.0 database, using the ReCiPe Midpoints (H). We calculated the values for the energy used in obtaining the materials used in manufacturing the final product based on the work from Suzuki and Takahashi (2005), and considering the information from the materials' datasheets. The task times considered were registered in labouratory conditions, as some of the processes are still in a research phase. The resources costs are presented in Table 3 and the vehicles emissions in Table 4.

Results and discussion

The analysis of the results considers that suppliers are reliable, and the manufacturing processes never stop. Demand is considered as stable. The model was simulated for a period of five years of operation. The results obtained from the simulation model are presented in Figure 3.

In what concerns to the total CO_2 emissions, see Figure 3(a), scenario 1 obtains the highest value. The highest contribution comes from the processing of the materials at the manufacturer. In Table 2, the values for the CO_2 emissions per material unit, and energy used per material unit are the highest in scenario 1, justifying the obtained results. Manufacturing also obtains the highest CO_2 emissions among the considered scenarios. Scenario 4 obtains the highest CO_2 emissions for transport activities. This is justified by the use of airplane, the vehicle with highest CO_2 emissions, as in Table 4, in the transport of the materials from the supplier to the manufacturer. Despite this, the best environmental performance is verified for scenario 4. Similar observations can be made from the energy use values in Figure 3(b), at the manufacturing process and material processing levels.

Table 2 – Model instances

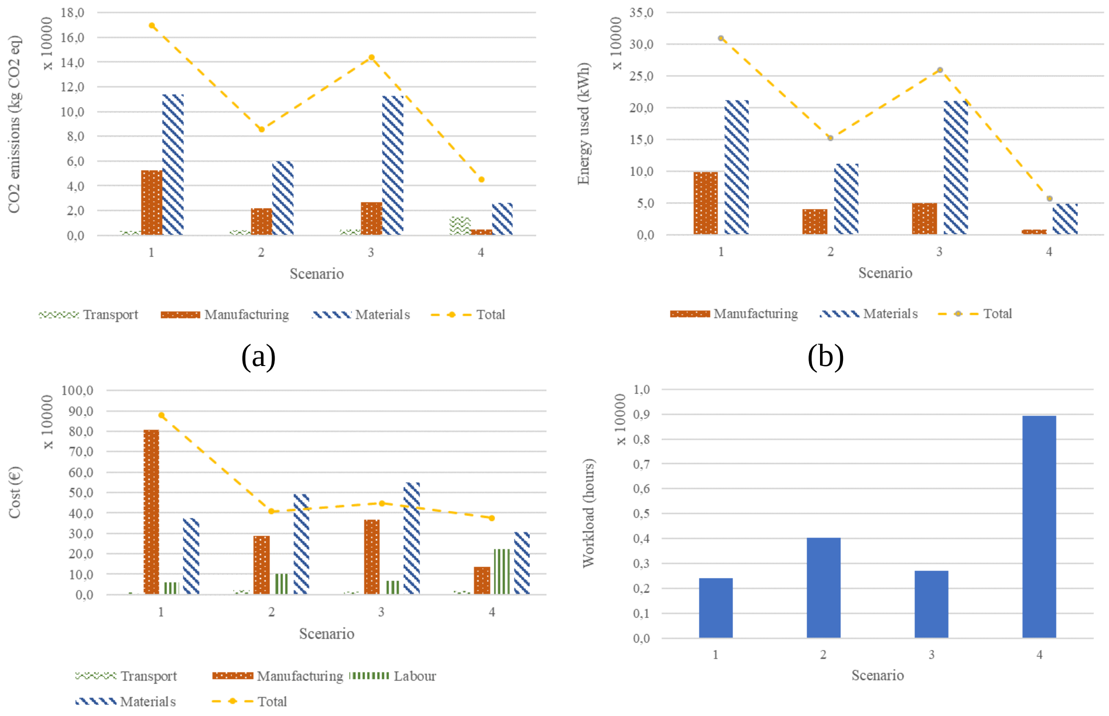
<table>
<tr><td>**Scenario**</td><td>1</td><td colspan="2">2</td><td>3</td><td>4</td></tr>
<tr><td>**Manufacturing process**</td><td>Bag molding</td><td colspan="2">VARI</td><td>VBO</td><td>Thermo-stamp</td></tr>
<tr><td>**Manufacturer location**</td><td>Europe</td><td colspan="2">Europe</td><td>Europe</td><td>Europe</td></tr>
<tr><td>**Process preparation time (hour)**</td><td>1.02</td><td colspan="2">3.16</td><td>2</td><td>4.25</td></tr>
<tr><td>**Process time (hour)**</td><td>5.33</td><td colspan="2">7.13</td><td>7.91</td><td>1.58</td></tr>
<tr><td>**Process finishing time (hour)**</td><td>0.17</td><td colspan="2">0.17</td><td>0.17</td><td>0.17</td></tr>
<tr><td>**Resources in manufacturing**</td><td>Workers, autoclave, vacuum</td><td colspan="2">Workers, oven, vacuum</td><td>Workers, oven, vacuum</td><td>Workers, oven, press</td></tr>
<tr><td>**CO_2 emissions per product ($kg\ CO_2\ eq$)**</td><td>26.06</td><td colspan="2">10.73</td><td>13.14</td><td>2.15</td></tr>
<tr><td>**Energy used per product (kWh)**</td><td>48.53</td><td colspan="2">19.99</td><td>24.47</td><td>4.02</td></tr>
<tr><td>**Vehicles used**</td><td>Refrigerated truck, Truck, Ship</td><td colspan="2">Truck, Ship</td><td>Refrigerated truck, Truck, Ship</td><td>Truck, Ship, Airplane</td></tr>
<tr><td rowspan="2">**Materials unit cost (€/unit)**</td><td rowspan="2">60.78</td><td>M1</td><td>M2</td><td rowspan="2">64.68</td><td rowspan="2">204.14</td></tr>
<tr><td>37.49</td><td>71.40</td></tr>
<tr><td rowspan="2">**Material use per product unit**</td><td rowspan="2">2.55 (m^2)</td><td>M1</td><td>M2</td><td rowspan="2">3.5 (m^2)</td><td rowspan="2">0.62 (kg)</td></tr>
<tr><td>4.99 (m^2)</td><td>0.22 (kg)</td></tr>
<tr><td rowspan="2">**CO_2 emissions per material unit ($kg\ CO_2\ eq$)**</td><td rowspan="2">18.40</td><td>M1</td><td>M2</td><td rowspan="2">13.30</td><td rowspan="2">17.30</td></tr>
<tr><td>4.46</td><td>11.34</td></tr>
<tr><td rowspan="2">**Energy used per material unit (kWh)**</td><td rowspan="2">34.30</td><td>M1</td><td>M2</td><td rowspan="2">24.80</td><td rowspan="2">32.22</td></tr>
<tr><td>8.30</td><td>21.11</td></tr>
<tr><td>**Supplier location**</td><td>Europe</td><td colspan="2">Europe</td><td>Europe</td><td>North America</td></tr>
<tr><td>**Customer location**</td><td>South America</td><td colspan="2">South America</td><td>South America</td><td>South America</td></tr>
</table>

Table 3 – Resources costs

Resource	**Cost (€/hour)**
Worker	25
Autoclave	70
Oven	20
Press	90
Vacuum	5

Table 4 - Vehicle CO_2 emissions

Vehicle	**Value (kg CO2 eq)/(km.kg)**
Refrigerated Truck	0.000373651
Truck	0.00021619
Ship	0.000021619
Airplane	0.00117



(a) (b)

(c) (d)

Figure 3 – Performance measures obtained for the four considered scenarios. (a) CO$_2$emissions (kgCO$_2$eq); (b) Energy used (kWh); (c) Costs (€); (d) Workload (hours).

The highest costs are verified in scenario 1, for which most of the contribution comes from the manufacturing process. In scenario 1, despite the autoclave not being the resource with the highest cost (Table 3), the process duration, in hours, is ten times higher than in scenario 4, where the most expensive resource, the press is used. In what concerns to the transport costs, scenario 4, registered the highest value. This is because the material supplier is in the USA, and the transport vehicle must cover a wider distance until reaching the manufacturer, when compared to the remaining scenarios, in which the supplier is located is Europe. Despite the material unit cost (Table 2) in scenario 4 being the highest, the highest material costs were registered in scenario 3. This is a consequence of the amount of material used in each final product. Scenario 4 registered the lowest costs, becoming the most economically attractive process, Figure 3(c), however, this process is more dependent on the workforce, registering the highest workload, as presented in the graphic from Figure 3(d). From a sustainability perspective, higher workload can mean more available jobs, however work conditions and the impact that these can have in the workers are not being considered. The process that is least dependent from the workers is in scenario 1, the bag molding process, with curing in autoclave.

Conclusions and future research directions

In this work we have developed a simulation approach for sustainability performance assessment in the aerospace SC. Our approach builds on existing work and considers each SC actor as an agent. Depending on the agent type, the internal behaviour can be defined by a SD model, DES model, or a statechart. Transport activities between the actors were modelled using DES. The model has been used for the sustainability performance assessment of different combinations of composites/processes in the aerospace industry. Metrics as CO$_2$ emissions, energy use, supply chain costs, and workload were assessed.

Within a context of NPD towards a sustainable supply chain, four products/processes were studied within the global supply chain. These are: bag molding with cure in autoclave, and OoA processes – VARI, VBO, and thermo-stamp.

Thermo-stamp process achieves the best sustainability performance levels in three of the registered measures – CO_2 emissions, energy use, and costs. However, this process is the least automatic, being responsible for the highest workload. Autoclave process is associated to the highest registered costs and the highest CO_2 emissions and energy use in manufacturing, transport, and materials processing at the supplier. Considering these results, scenario 4 becomes the most attractive however, further studies should be conducted to assess the effect that a lower process automation can have in the overall quality of the finished products. An assessment of the work conditions, associated to the workload levels obtained, should complement the analysis of the results.

The presented approach as mentioned above explores the developed model using as basis process times obtained in labouratory conditions. As future work the scale-up of the processes to obtain more realistic processing times should be performed. Also, to take a better advantage of a simulation approach for the sustainability performance assessment in the aerospace SC, scenarios of uncertainty associated to suppliers, manufacturing process, and demand should be considered. Furthermore, other performance metrics should be assessed for deriving more relevant managerial implications from using the different processes.

Acknowledgements

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Paper G

Sustainability performance assessment in the commercial aircraft MTO supply chains: a hybrid simulation approach applied to the real case of an aerospace manufacturer

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Abstract - Make-to-Order (MTO) supply chains (SCs), common in industries as the aerospace, have become a recent focus of attention due to the growing relevance of the product customization activities. The complexity of these manufacturing SCs, allied to the major differences when compared to mass manufacturing (e.g. demand volume), and the varied manufacturing activities that exist, call for the use of tailored solutions for performance assessment, where a critical sustainability perspective should be considered. Given this, and using simulation as a research method, it is the purpose of this work developing a hybrid and hierarchical performance assessment model, considering key sustainability indicators. The model is hybrid due to the use of different simulation methods - System Dynamics, Discrete Event simulation, and Agent-based simulation – and is hierarchical due to the different levels of analysis considered and details for the models. Unlike existing contributions, this work adresses the MTO supply chain from a sustainability performance perspective and considers the wide supply chain perspective without the need to compromise the representation of the diverse manufacturing functions and resources. A multi-criteria decision analysis complements the analysis of the simulation results. The model is applied to the real case of an aerospace manufacturer, to assess the sustainability performance of alternative SC structures imposed by the introduction of different combinations of manufacturing processes and supply of composite materials. Relevant performance indicators are assessed for scenarios of uncertain demand and supply of materials for each combination of manufacturing processes and composite materials, and the outcomes of the decision-making process for decision-makers (DMs) with different profiles are considered.

Keywords - Aerospace, Hybrid simulation, Make-to-order, Supply Chain, Sustainability performance

1. Introduction

In the contemporary manufacturing context, the make-to-order (MTO) manufacturing strategy has become increasingly relevant. For companies operating under this strategy, it is beyond the bounds of possibility accurately forecasting demand, ordering materials or producing in advance (Stevenson, Hendry, and Kingsman 2005), which requires highly flexible operations (Yiyo et al. 2016). It is utterly important that companies establish complex trade-offs between their operational settings and the response to the customer (Richard 1998). With a usually low production volume, MTO supply chains (SCs) are responsible for delivering customized, complex, and high margin products, able to meet individual customer requirements, while keeping the product design within established specifications (Euthemia and Mark 2010). Examples of sectors in which the MTO strategy is commonly applied include the aerospace, shipbuilding, machinery, medical and construction equipment industries (Li and Womer 2012).

Given the relevance of tackling the wide MTO SC spectrum to achieve competitive advantage, a close monitoring and assessment of performance is critical. When the external SC level is considered, measuring performance not only encompasses considering multidimensional indicators that span across different companies and target a great panoply of tasks as logistics, inventory management, demand forecasting, supplier and customer relationship management (Maestrini et al. 2017), customer-oriented internal SC activities as component manufacturing and assembly (Hicks, McGovern, and Earl 2000), but also the business sustainability. This is a vital dimension of the SC performance, with the aim of sustaining the welfare of the economy, the environment, and the society: the triple bottom line (TBL) (Hassini, Surti, and Searcy 2012; Barbosa-Póvoa, da Silva, and Carvalho 2018). Integrating environmental and social aspects, alongside the economic dimension has been gaining wider acceptance for the managerial decision-making process (Brandenburg et al. 2014).

Though the sustainable SC management (SSCM) has been increasing in relevance, few formal/quantitative models have been proposed in the literature; which contrasts with the wide realm of research in the non-sustainability modelling field (Barbosa-Póvoa, da Silva, and Carvalho 2018). For industries as the aerospace, which has been progressively engaging in new product development efforts to achieve more sustainable operations and supply chains

(Tang, Zimmerman, and Nelson 2009), this limited research can become problematic. For these MTO industries, whose dynamics and needs have been seldom addressed, further research is needed alongside the development of more formal/quantitative models for SSCM. This work contributes to the literature by addressing these two challenges in a combined way, by answering the following research question:

How to include a sustainability-oriented perspective on the operational performance assessment of MTO SCs?

The increasing complexity of modern manufacturing systems and the mutual impacts that different parts of an organization have, call for the use of hybrid simulation approaches to target different problems within the same system (Jahangirian et al. 2010), capable of capturing the spectrum of enterprise-wide solutions (Glazner 2009). Hybrid approaches use at least two of three simulation methods – System Dynamics (SD), Discrete-event Simulation (DES), and Agent-based Simulation (ABS) (Swinerd and McNaught 2012).

A hierarchical and hybrid simulation model, using SD, DES, and ABS, for the operational performance assessment prediction of MTO SCs that considers the economic, social, and environmental sustainability dimensions is proposed in this work, which follows the works by Barbosa and Azevedo (2018b) and Barbosa and Azevedo (2018a). The proposed approach helps accessing relevant sustainability metrics alongside operational business metrics, for comparing different SC operational scenarios. The goals of this study include:

- Develop a hybrid simulation model for the MTO SC performance assessment by focusing on the strengths of the different modelling and simulation methods, and considering the key requirements set by the gaps identified for the SC sustainability models;
- Apply the developed model to a real aerospace MTO SC;
- Derive the adequate performance indicators for assessment, based on three pillars of sustainability and the requirements of the case study;
- Make computational experiments to assess the relevant performance indicators and show the potential of the proposed method as a decision support tool;
- Use a Multi-Criteria Decision Analysis (MCDA) to predict the possible outcomes of the decision-making process for the performance measures obtained through the hybrid simulation model, while considering different decision-makers (DMs) profiles.

This paper is structured as follows. Section 2 presents the literature related to the MTO SC, targeting its main features and requirements. The different mathematical models used for the sustainability dimension at the SC level are explored, and an overview of the sustainability metrics is also included. Section 3 presents the detailed explanation of the proposed model and in section 4 the application case and model instances are presented. Section 5 delves of the obtained results and discussion, and the paper ends in section 6, with the main conclusions, research implications, and future research directions.

2. Related Literature

The proposed approach uses hybrid simulation applied to the sustainability performance assessment of the MTO SCs, as appropriate to different levels of detail required for the varied SC activities. The following sub-sections tackle the use of simulation for MTO SCs, a specification of the main features of the different simulation methods and the potential of hybrid simulation approaches. Also relevant to this work, and addressed in the following sub-sections, are the quantitative models for the SC sustainability and the relevant performance metrics.

2.1. Simulation models for MTO supply chains

As defined by Amaro, Hendry, and Kingsman (1999), MTO production “concerns manufacturing a standard product (any customisation is nominal and does not increase total lead-times) only on receipt of a customer order or against an agreed schedule or call-off”. Hence, for companies following an MTO strategy, the customer orders are triggers for the material flows (Yiyo et al. 2016) and production is delayed until a customer order has been received (Hilletofth 2009).

There are three main sources of uncertainty for MTO SCs: demand (customers), the manufacturing system (manufacturer), and the supply of materials (suppliers). Variations in demand and supply of materials may lead to major unpredictable effects and SC destabilization. Manufacturers following an MTO strategy are often in stockout risk (Tseng, Gung, and Chun-Che 2013), and cannot immediately satisfy customer orders. As the customer is exposed to the entire order lead time (Akinc and Meredith 2015), planning and control methods are key for a high delivery performance (Beemsterboer et al. 2017).

Though several authors have been focusing on the performance assessment of MTO SCs, through quantitative modelling approaches, the literature still presents some major drawbacks (Chan and Chan 2010). Mathematical programming approaches often use deterministic parameters (e.g. demand) to achieve optimal solutions, ignoring the uncertainty and the systems' dynamics. When these stochastic parameters are contemplated, there is no possibility of achieving optimal solutions. At the SC level, suppliers are unrealistically considered to have infinite capacity. As for simulation-based performance assessment, it provides a dynamic and predictive capability for the study of the whole SC.

Simulation is the most effective method for assessing the performance and design of SCs (Rabelo et al. 2015), and it supports the design and management of decisions in all their complexity, and in a stochastic context (Riccardo et al. 2005). It is a powerful research technique that allows looking at an artificial world moving forward into the future, giving an unprecedented opportunity to intervene and attempt to make improvements to performance (Dooley 2002), even prior to the implementation of the real system (Robinson 2004). Simulation gives a great opportunity to create knowledge about the systems, through the structured analysis of issues about the system being modelled (Robinson 2004), and gives the needed flexibility (Stefanovic, Stefanovic, and Radenkovic 2009; Glazner 2009) for exploring complex systems under different scenarios, through a "What-if?" analysis (Stefanovic, Stefanovic, and Radenkovic 2009). Real-life phenomena can be represented in different ways, depending on the type of simulation method that is used for that representation. There are three main simulation methods, whose features are important to understand: SD, DES, and ABS.

2.1.1. System Dynamics

SD modelling and simulation uses feedback loops to represent the model's dynamic complexity (Lättilä, Hilletofth, and Lin 2010), and is usually applied for the modelling of large systems through a continuous representation of time (Jain et al. 2013).

It uses stocks, flows between the stocks and feedback loops for the representation of the different processes. Upon the computer implementation, these structures are converted into finite differential equations that capture interactions between parts in a system, the influence of delays (Sterman 2000; Jain et al. 2013), and that calculate how the varied system parameters behave over the simulation time horizon (Jain et al. 2013).

Models built using SD are deterministic (Heath et al. 2011) and excel at representing systems at a high abstraction level (Borshchev and Filippov 2004). Common applications of SD include SCs, economics, innovation, workforce management, and markets (Lättilä, Hilletofth, and Lin 2010). SD models are unable of mapping discrete events, and their deterministic structure reduces the model flexibility (Schieritz and Gröβler 2003).

2.1.2. Discrete Event Simulation

In DES, entities flow through blocks of activities, delays, queues, are processed, seize, and release resources (Borshchev and Filippov 2004). Time is represented as a discrete series of events and is used to model systems in a medium to low level of abstraction (Jain et al. 2013).

Systems are modelled from a macroscopic point of view and the models require a high volume of accurate data or estimates about the systems operations. This method has been widely applied in the literature for the representation of the operational level of organizations (Jovanoski et al. 2012), and in logistics (Borucki, Pawlewski, and Chowanski 2014). In practical applications, DES is often used for the near real-time decision-making in manufacturing (Jain et al. 2013).

2.1.3. Agent Based Simulation

ABS is a method commonly used for representing dynamic and adaptive systems, whose behavior is given by the interactions amongst independent entities (Jain et al. 2013). In these models, the agents' behavior and their interactions with the surrounding environment follow logic rules (Wang, Zheng, and Zhao 2013).

An agents' internal state is dynamic and evolves as experiences accumulate with time (Heath et al. 2011). As many details as possible represent the individual features of the system elements (Martinez-Moyano et al. 2007). An increasing use of ABS is being verified in business related areas, including manufacturing, maintenance and SC management (Lättilä, Hilletofth, and Lin 2010). ABS has been applied in the modelling of SCs, particularly by representing each supply chain node as an individual agent (Jain et al. 2013).

2.1.4. Simulation in MTO

From the above, it is not surprising that upon considering practical and real-world applications, in which the complexities of the whole enterprise and multiple levels of decision-making need to be addressed, simulation techniques come at great relevance and appropriateness (Jahangirian et al. 2010). For the MTO SCs, Table 1 shows examples of simulation models that have been proposed in the literature and that can be used for performance assessment.

Table 1. Examples of simulation models for MTO SCs

Application	**Simulation method(s)**	**Level of analysis**	**Sector**	**Reference**
Manufacturing planning and control	DES	Facility	Capital goods industry	(Hicks and Braiden, 2000)
Market forecasting and structural analysis	SD	Market	Commercial aircraft industry	(Lyneis, 2000)
SC behavior and performance analysis	SD	SC	Generic MTO SC	(Özbayrak et al., 2007)
SC management	SD-DES	SC	Generic manufacturing SC with suppliers providing parts in an MTO basis	(Umeda, 2007)
Enterprise modelling and identification of improvement opportunities	SD[2]	Enterprise	Electrolytic capacitor industry	(Zhen et al., 2009)
Performance assessment	ABS	SC	Generic MTO SC	(Chan and Chan, 2010)
Production planning	DES[1]	SC	Generic MTO SC	(Hachicha et al., 2010)
SCs with dynamic structures	ABS	SC	Generic MTO and Make-to-Stock (MTS) SCs with dynamic structures	(Li and Chan, 2013)
Value network modelling and simulation for strategic decision-making	DES	Value network	Shoemaking industry	(Daaboul et al., 2014a)
Performance assessment	DES	Value network	Shoemaking industry	(Daaboul et al., 2014)

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[2] Other analysis methods are used in conjunction with the simulation method(s)

Performance assessment	SD-DES-ABS	Internal SC	Advanced MTO/ETO manufacturing (intralogistics solutions manufacturer)	(Barbosa and Azevedo, 2018b)
Performance assessment	SD-DES-ABS	External SC	Advanced MTO/ETO manufacturing (intralogistics solutions manufacturer)	(Barbosa and Azevedo, 2018a)

Despite valuable, the approaches presented in Table 1 still fall short in considering all relevant problems of SCs, and some challenges remain to be addressed. While a SD approach, as in Özbayrak, Papadopoulou, and Akgun (2007) gives a static SC perspective, which reduces the model flexibility, an approach based on a pure ABS method as that in Li and Chan (2013), or a pure DES method, as in Daaboul, Castagna, et al. (2014), requires much data, and associated great efforts for the data collection. Standalone simulation approaches may hinder the more holistic or detailed analysis of the system, reducing the flexibility of the developed models. Also, there is the need to add a sustainability perspective to the performance assessment, which none of the simulation models in Table 1 consider and, contemplate the more detailed role of some key resources in MTO SCs (e.g. transport resources). In Barbosa and Azevedo (2018a), though the external MTO/ETO external SC is considered, there is no focus in the logistics functions and resources. Additionally, the models presented in Barbosa and Azevedo (2018b) and in Barbosa and Azevedo (2018a), by choosing DES for representing production and assembly, assume that complete information about these functions is available. Though DES has proven to excel at modelling functions at this operational level (Borshchev and Filippov 2004), the high data demands of DES (Heath et al. 2011) may be prohibitive for the modelling and simulation process. Hence, an alternative SD approach, which considers a holistic view for the production functions becomes a valid alternative as will be explored in this work.

As above referred, standalone simulation may not appropriately respond to the demands of modern and complex manufacturing systems (Barbosa and Azevedo 2017). As noted by Jahangirian et al. (2010), there has been a growing trend in the use of hybrid simulation approaches fueled by the fact that enterprise-wide solutions are increasingly relevant and the belief that the different parts of an organization, though different in their structure, will have mutual impacts. By simultaneously using different simulation methods, problems of over complex models or improper use of the methods can be overcome (Schieritz and Größler 2003), and a more natural representation of the systems can be accomplished.

As we are addressing a very complex problem structure, which is the MTO SC, its dynamics, and its multidimensional performance assessment, hybrid simulation is used. The above gaps are considered in our contribution, by providing a hybrid simulation model that addresses sustainability issues in the MTO SCs, and that considers the detailed role of key resources and a holistic view of the systems.

2.2. Sustainable supply chain performance: quantitative models and metrics

Sustainability, in its TBL approach has seen an outstanding growth in the past decades (Brandenburg and Rebs 2015). When it comes to sustainability, companies are increasingly pressured to look at their entire SCs, while attempting to remain competitive (Mota et al. 2015). There are major contributions to the sustainability realm when addressing the SC, especially as comprehensive processes, from the initial processing of the raw materials, until the delivery to the final customer, are considered (Houda and Said 2011). It is not surprising that the integration of the TBL for organizational sustainability has been gaining increasing relevance for the managerial decision-making (Brandenburg et al. 2014).

2.2.1. Quantitative models in supply chain sustainability

Formal quantitative models in sustainability intend to characterize the real systems through a simplified version of sets of variables and their causal relationships (Brandenburg et al. 2014). Despite this, sophisticated approaches that represent stochasticity and uncertainty are still belittled (Brandenburg and Rebs 2015). Likewise, key SC activities, as the transportation, have been neglected in the literature (Brandenburg et al. 2014).

The mathematical models for SC sustainability are often developed considering a focal company that is connected with the suppliers and customers through products and processes (Brandenburg and Rebs 2015). As identified by Brandenburg et al. (2014) and Barbosa-

Póvoa, da Silva, and Carvalho (2018), there are several modelling approaches in the literature, as life-cycle assessment (LCA) models, equilibrium models, multi-criteria decision making, analytic hierarchy process (AHP), simulation, and heuristics. Simulation for sustainability has often been used due to the need to complement traditional LCA approaches, with a dynamic and time behavior (Moon 2017).

Dou and Sarkis (2010) proposed a framework based on Analytical Network Process (ANP) for incorporating relevant factors, as the facility location, outsourcing and sustainability, in the strategic offshoring decision; Mota et al. (2015) and Mota et al. (2018) proposed a generic multi-objective mathematical programming model for the design and planning of closed loop SCs, which integrated metrics across the three dimensions of sustainability. Saint Jean (2008) presented a SD model for studying the evolution of two populations of vertically related firms that had to cope with the environmental quality demand. Also, using an SD approach, but associated to the TBL, Lee et al. (2012) developed a model for the evaluation of the dynamic and multidimensional features of Product Service Systems (PSS). Mantese and Amaral (2018) used an ABS simulation approach for the assessment and development of industrial symbiosis indicators. Hybrid simulation approaches have been used by Jain, Lindskog, and Johansson (2012) for estimating the carbon footprint of products flowing through a SC; Jain et al. (2013) used a hierarchical approach to assess the energy consumption needed to keep products flowing through a SC; Wang, Brême, and Moon (2014) used hybrid simulation as a complement to LCA; and Abduaziz et al. (2015) assessed green logistics practices in the automotive industry.

Given the need to develop more sophisticated approaches for decision-support in the SSCM domain, as dynamic programing, SD, ABS, and evolutionary algorithms (Taticchi et al. 2015), the role of simulation has been highlighted in a publication by Moon (2017). Hence, simulation approaches for the SC sustainability performance assessment should be considered. Hybrid simulation approaches, which are a growing trend in the literature must also addressed, as there may be the need to handle different levels of model granularity and/or achieve increased levels of flexibility, as provided by the use of different simulation methods (Moon 2017). The different papers within the hybrid simulation for sustainability (Jain et al. 2013; Jain, Lindskog, and Johansson 2012; Wang, Brême, and Moon 2014; Abduaziz et al. 2015; Elia, Gnoni, and Tornese 2016), through different model designs, have proven to excel at assessing multiple sustainability related topics.

2.2.2. Sustainability performance indicators

When performance assessment extends to the SC level, multiple managerial perspectives must be considered to enhance the SC efficiency (Balfaqih et al. 2016). The selection of the performance indicators at the SC level is critical because the system being analysed is very large and complex (Beamon 1999). Indeed, assessing the SC performance means considering the performance of many tasks, including logistics, inventory management and warehousing, demand forecasting, and supplier and customer relationship management. The multidimensional indicators adopted for the SC performance measurement systems span across different firms and processes (Maestrini et al. 2017; Tanzil and Beloff 2006), and when sustainability is considered, the metrics give insight into the impact of the relative contribution of the different SC stages in e.g. in the energy use, waste generation, and greenhouse gas (GHG) emissions (Tanzil and Beloff 2006). The performance indicators must be established in a sector-by-sector or case-by-case basis (Clift 2004).

Indicators are key in the practice of performance monitoring and assessment, and in the decision-making process, especially the quantitative measures (Popovic et al. 2018). When it comes to the sustainable development, performance indicators should reflect a good balance between the economic development, environmental stewardship, and the social equity – the TBL (Sikdar 2003). However, as many authors have noticed (Moon 2017; Popovic et al. 2018; Mota et al. 2015; Brandenburg and Rebs 2015; Mota et al. 2018; Barbosa-Póvoa, da Silva, and Carvalho 2018), the social dimension of sustainability is the least studied among the three pillars of the TBL.

As exposed by Clift (2004), the Global Reporting Initiative (GRI) proposed an approach to derive sustainability indicators, that starts from broad categories, through aspects and ending with specific indicators. As the author reports, categories are broad areas of issues related to environmental, social, and economic concerns of stakeholders; aspects are the types of information within a category, and indicators are the measurements of a given aspect.

In the context of this work we follow the idea by Clift (2004), stating that the performance indicators should be derived in a case-by-case approach, and the GRI approach of defining categories, aspects and indicators for the sustainability realm. Other indicators which are relevant for the MTO SCs as the tardiness in the deliveries, resources utilization, inventory levels (Barbosa and Azevedo 2018b), and an assessment of the orders waiting to be processed, will also be evaluated.

3. The proposed hybrid MTO supply chain model

The goal of the present study is to evaluate the sustainability performance of the MTO SCs under various scenarios. The problem is addressed through a hybrid modelling and simulation approach, using well proven simulation methods – SD, DES, and ABS. We follow a top-down approach, by starting with the macro analysis of the SC actors, and afterwards delving on the functions which are modelled within each actor. The model allows considering different levels of functions detail, as it uses different modelling and simulation methods and is based on previously published works, Barbosa and Azevedo (2018b) and Barbosa and Azevedo (2018a).

Notwithstanding this, the proposed model focuses on the pure MTO SC, gives higher emphasis to the logistics function, which have been neglected and attempts to provide a more aggregated and generic view of the production functions, overcoming potential problems with case study data unavailability. The model considers the following:

- Four SC actor types: the supplier, responsible for supplying materials and components; the manufacturer, responsible for the manufacture of the final products; the customer, the demand driver in the model, and the final destination of the end products; and material transfer points (MTPs), which are used when the materials, components, or final products have to be transported among SC actors which are located in different continents, requiring the use of more than one transport type to ensure the exchange of the physical goods;
- Each SC actor is modelled as an agent, to improve the model flexibility and have the possibility of modelling SCs with different structures using the same model;
- The agents' internal functions are classified as interface functions, planning/control, and production;
- Transport resources, which permit the flow of materials in the SC, are also modelled as agents, but these exist inside the SC actors and not as isolated agents in the model;
- Agents are positioned in Geographic Information System (GIS) map that provides relevant information during the model execution, as the distance between the agents, and has a key role in simplifying the logistics functions;
- Events and shared variables allow the exchange of information among models from different methods;
- The model is built from the manufacturer perspective, the focal SC actor, and considers the forward SC.

3.1. Agents' communication overview and methods' integration

The data flow diagram in Figure 1 shows the information and material flows in the model. The customer is responsible for triggering all activities in the SC. When it needs a product, an event is triggered for placing an order to the manufacturer. Planning and production at the manufacturer start after an order is received. If needed, the MTO manufacturer purchases materials from the suppliers. The suppliers internally assess the possibility of fulfilling the manufacturer orders. Following Figure 1, information flows from the customer to the manufacturer and from the manufacturer to the supplier. Materials flow in the opposite direction. Materials can pass through MTPs when more than one transport type is required. The transport can be direct, when there is no need to use MTPs, and indirect, when MTPs are needed. The use of the MTPs occurs when the agents between whom materials or final products are exchanged are in different continents.

The interface functions insure that proper communication occurs. These provide critical information to planning and control. While different simulation methods are used in the modelled functions, it is important to clarify how the models from different methods have been integrated, as in Figure 2. The model is built considering a generic agent-based structure. Agents can effectively represent SCs, in which each SC node is an agent that interacts with the other agents and the environment through discrete events. Though each SC node is an agent, there may be different levels of visibility and information for the different nodes, which hinders the detailed modelling of all the behaviors in the SC (Tan, Cai, and Zhang 2017). This is why a hybrid simulation approach brings advantages, by allowing the modelling of the different activities inside the agents with different degrees of detail, and in a hierarchical fashion. By establishing an overall agent-based structure for the model it is possible to simulate SC nodes whose behavior is established with different degrees of detail, depending on the visibility of the information or other relevant features. Furthermore, the use of a generic agent-based approach facilitates the establishment of the information flows among the modelled and simulated SC nodes.

Production functions are simulated using an SD approach and transport using DES. Business rules are responsible for the planning/control functions, for calculating the values of the variables exchanged among the functions or setting the conditions for triggering the events (e.g. start and end of transport). Transport resources have an internal structure defined by a set of states, and the orders, though defined as agents, are passive elements exchanged among key SC actors. These are the least detailed element in the model. Despite the core activities of the manufacturer and supplier being defined by an SD model, the transport activity inside these agents is modelled using a DES approach. Hence, as represented in Figure 2, there is an overlap between SD and DES, which represents the start of the transport activities following the production.

In the following sub-sections, each of the agents, their internal functions, and justification for the use of the different modelling methods, are explored.

3.2. The customer agent

3.2.1. Interface functions

The customer interface functions are responsible for the interactions with the manufacturer. These ensure that the customer orders and receives the products. Two functions have been implemented, triggered by the action of events: one for the ordering and other for receiving the products. Upon the triggering of the product ordering event, the customer generates a new order, with the features amount, period desired for receiving the order, and product identification.

Physical interactions with the manufacturer are established upon receiving the product. For identification and proper delivery, the product owns the features of the order sent by the customer. Upon receiving the product, and for monitoring the manufacturer compliance with the delivery dates, the customer registers if the delivery was on time or late.

3.2.2. Planning/control functions

At the customer level, planning and control functions are not critical, as the specific manufacturing activities of the customer are not modelled. However, the customer orders according to its business needs. To simulate the varied business needs, a random number generator is used to simulate the number of products being ordered by a customer.

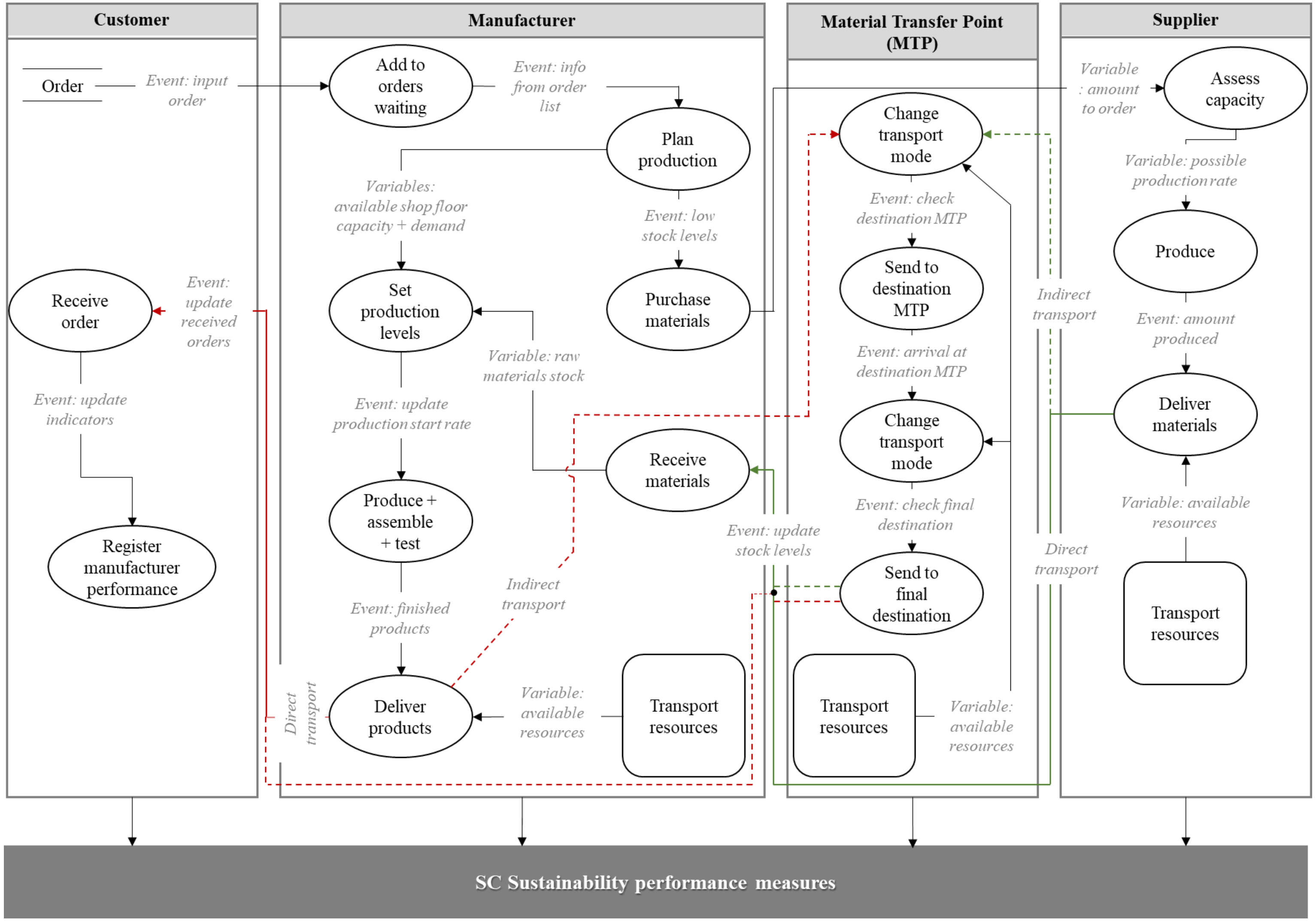


Figure 1. Simulation data flow diagram.

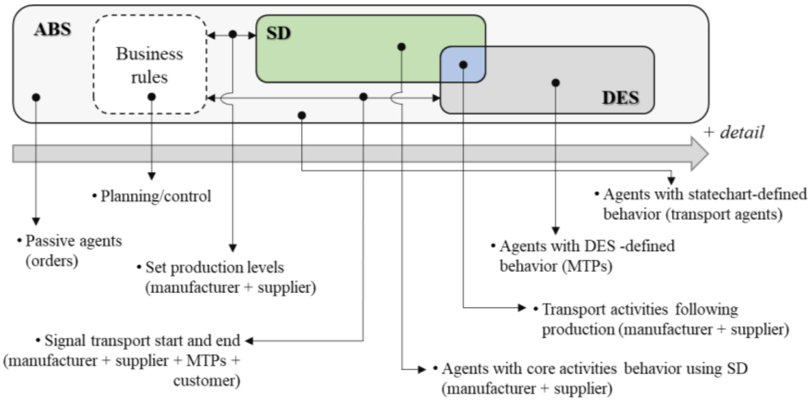


Figure 2. Integration of the methods in the simulation environment.

3.3. The manufacturer agent

3.3.1. Interface functions

The manufacturer must establish interactions with suppliers and customers. On the customer side, the manufacturer receives product orders and delivers the manufactured products; while on the supplier side, the manufacturer orders materials and/or components, and receives the ordered materials and/or components from the suppliers.

When the manufacturer receives an order, it adds the order to the list of orders waiting to be processed. The orders are positioned in this list in the order these are received, which can be easily changed to consider other priority rules. When a new order enters the list, the manufacturer plans its execution. Upon finishing the production of the products in an order, the manufacturer sends them to the customer. Sending the produced products to the customer considers that the order will be introduced into a transportation model, developed using DES, as described in sub-section 3.6.

Upon planning production, the manufacturer assesses the need to order materials and/or components to fulfil the customer orders. When the materials and/or components in stock are not sufficient to fulfil all demand, the manufacturer places an order to the suppliers. Ordering the materials may consider a minimum order quantity (MOQ). The material ordering policy can be changed, depending on the requirements of the case study to which the model is being applied. Upon receiving the deliveries from the suppliers, the stock of materials at the manufacturer increases in the same amount as that delivered by the supplier. This is important, as the supplier may not respond to the full manufacturer demand in a single delivery.

3.3.2. Planning/control functions

The planning/control functions at the manufacturer correspond to the production planning, ordering of materials/components from suppliers, setting and monitoring the production levels to assess when a customer order has been fulfilled, or when the production rate must be updated. High-level business rules have been used for planning in periods of one month. The following pseudo-code shows the implemented planning function:

```
initialize material_requirements, promised_materials, remaining_materials, materials_to_order, period_to_start_production, period_to_finish_production, available_periods, order_amount, period_orders, production_rate, added_amount, period_production_rate to zero

assess the order_amount

calculate material_requirements as the product of order_amount by the materials used per product

calculate promised_materials //materials in stock to be used in other orders

calculate remaining_materials as the sum of the existing stock and materials on order minus the promised_materials

calculate materials_to_order as the maximum between zero and the difference between the material_requirements and the remaining_materials

if materials_to_order is higher than zero

    assess the product amount that can be produced from the existing stock

    set period_to_start_production of the remaining products to the current simulation period summed to the expected delay for obtaining materials

    order materials_to_order

else

    set the period_to_start_production to the current period

set period_to_finish_production to the period set by the customer

calculate the available_periods as the difference between the period_to_finish_production and the period_to_start_production

calculate the period_orders as the ratio between the order_amount and the available_periods

while order_amount is higher than zero

    for the simulation periods

        if period_orders are lower than the maximum period production

            calculate added_amount as the minimum between the period_orders, the order_amount, and difference between the maximum period production and the period_orders

            decrease period_orders by the added_amount

            decrease the order_amount by the added_amount

calculate and set the period_production_rate as the ratio between the period_orders and the period time units
```

Monitoring the production levels is performed using a condition triggered event that updates the production levels every time a new unit is produced. Setting the desired production rate is an event that occurs for each new simulation period, to update the desired production rates calculated using the planning function.

3.3.3. Production functions

Modelling production/manufacturing activities in the model was performed using SD. Despite DES being the most widely used method for operational systems analysis, it is not in the scope of this work a detailed mapping of the manufacturing processes, but rather achieving a system wide perspective. Representing the production processes using DES requires much data to be used (Heath et al. 2011), which may be prohibitive when there is few information about the system or it is not implemented yet. Despite the common applications of DES in streamlining and validating processes, we have decided to use SD, so a global understanding of the production system can be attained (Kibira, Jain, and McLean 2009). This is a different view from that considered in (Barbosa and Azevedo 2018b, 2018a), where complete information about the production system has been considered to exist. Stock items in the SD production model, the products produced, will be indistinguishable and passive, meaning that no gains would be achieved by using ABS (Borshchev and Filippov 2004).

For modelling the production system, it is necessary to consider many elements required for the production activities. These elements determine the production levels and include the machine's capacity, the number of workers, and the manufacturing technology (Kibira, Jain, and McLean 2009). The manufacturing model is based on the policy structure of inventory and production proposed by Sterman (2000), and is presented in Figure 3. The equations associated to the SD model in Figure 3 are presented in Table A. 1 from appendix A. The stock and flow diagram considers that the manufacturing process is divided into three stages: the setup, the process, and the finishing activities. There is a stock of raw materials which is depleted when using the materials for manufacturing. The materials can become obsolete due to their shelf life. The model parameter, desired production start rate, conditioned by the demanded products, is updated through an event in every new simulation period and is shared by the production and planning/control functions. The production start rate is conditioned by the desired start rate, the levels of raw materials stock and by the setup capacity. The process time is determined by the time needed for the process and its capacity. The finishing rate depends on the time needed for the finishing activities.

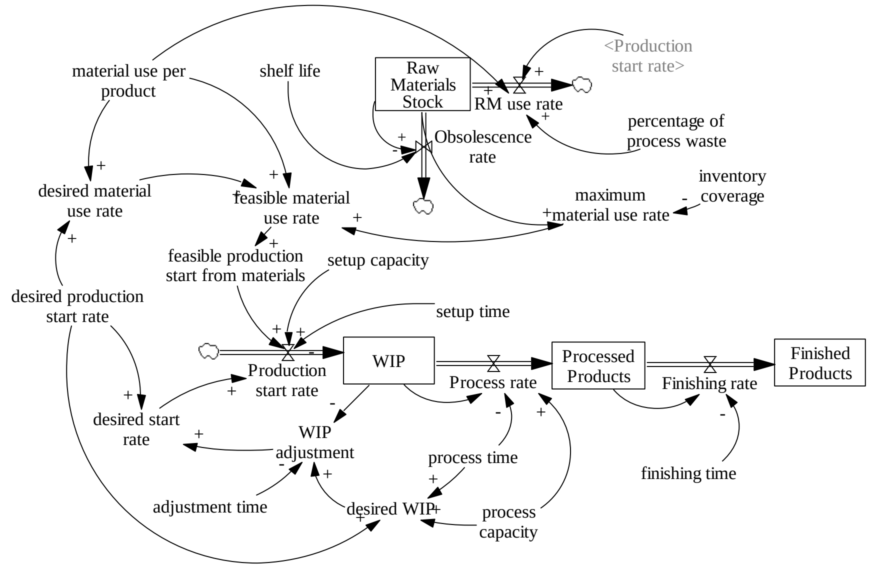


Figure 3. The SD policy structure of inventory and production of the manufacturer agent (adapted from (Sterman 2000)).

Despite the customization activities being relevant for an MTO manufacturer, these are not explicitly modelled in this context. We are assuming that these activities will not interfere with the production activities and that when customized designs are needed, these are are nominal, do not increase the lead times, and are automatically generated by appropriate software resources. Previously published work addresses this problematic in ETO manufacturing environments Barbosa and Azevedo (2018b) and in Barbosa and Azevedo (2018a).

3.4. The supplier agent

3.4.1. Interface functions

At the supplier, interface functions must ensure proper communication with the manufacturer. The supplier receives the orders for materials from the manufacturer and must deliver these. Two functions have been implemented, one for receiving the materials orders and other to send the materials to the manufacturer.

Upon receiving an order request from the manufacturer, the supplier agent assesses the amount to be produced, and if this amount can be delivered in a single delivery. This is imposed by the capacity of the transport agents. If the manufacturer orders an amount higher than the transport agent capacity, the supplier divides the order in multiple orders. After the delivery occurs, and by the action of an event, the stock of materials at the manufacturer increases in the same amount as the materials delivered by the supplier.

3.4.2. Planning/control functions

The planning/control functions at the supplier correspond to production planning, monitoring and setting production levels to assess when a manufacturer order has been fulfilled, or when the production rate must be updated. High-level business rules have been used for this function. The supplier splits the production through the simulation periods to fulfil the manufacturer order. Production rates are updated at the beginning of each simulation period and limited by the available capacity.

3.4.3. Production functions

A SD stock and flow diagram has been implemented at the supplier to simulate the production activities. This model considers the desired production rates as calculated by the planning/control functions and a maximum possible production rate. The maximum possible production rate is a random variable that simulates occupied capacity at the supplier, and limits its possibility of responding to the manufacturer demand.

3.5. Material transfer points

The behavior of the MTPs has been implemented in DES. DES has been selected considering its strengths in modelling and simulating the logistics activities (Borucki, Pawlewski, and Chowanski 2014). As there is an urgent need to highlight the role of the transportation activities for sustainability purposes (Barbosa-Póvoa, da Silva, and Carvalho 2018), the use of a simulation method that allows a more detailed system analysis is justified. When the agents between whom materials and final products are exchanged are in different continents, different transport agents are used. Transferring materials and final products between transport modes occurs at seaports and airports. The DES model determines if the materials or final products are being transferred from a truck to a ship or an airplane, or from an airplane or a ship to a truck.

3.6. Transport agents and functions

Each transportation resource is an agent. These exist in limited number inside the supplier, manufacturer, and MTPs. The vehicles receive information from their owners to transport materials and final products. Their action is represented by five internal states: at owner, loading materials/final products, going to the specified final location, unloading materials/final products, and returning to the owner.

4. Case study – Sustainable SC for the commercial aircraft industry

The hybrid performance assessment model has been applied to a real SC. In this section we describe the focal SC node (manufacturer), the problem being analyzed, and the problem instances used in the model. A set of case scenarios is introduced.

4.1. Company description and problem analysis

In the aerospace industry different factors, including the need to reduce fuel costs through the reduction of the airplane's weight, have been pushing aircraft manufacturers to produce more efficient airplanes, through more efficient SCs. To achieve this, there has been a commitment of Original Equipment Manufacturers (OEMs) and their SC partners in reducing the airplane's weight using composite materials in the aero structures (Tang, Zimmerman, and Nelson 2009).

The case study focuses on a key supplier in the aerospace industry, henceforth called AeroSup. It produces critical, highly complex, and high size aerostructures using carbon-fiber composites; it supplies an airframe OEM. Though producing standard structures, with fixed designs, given the high size and value of the final product and the erratic and low demand volume, AeroSup produces to order, making use of an MTO strategy. Given the industry requirements demands, AeroSup must maintain its composite manufacturing processes updated and compliant.

Recently, and given the relevance of composite materials for the future of the aerospace industry, AeroSup became interested in updating its composites manufacturing process to achieve a more sustainable SC. Up to now, AeroSup has been using a composite manufacturing process that is based on an autoclave curing technology that, despite providing top quality products, entails high manufacturing costs and consumes many resources. In pursuit of implementing a more sustainable SC, AeroSup is interested in assessing the impact in the SC sustainability of different composites manufacturing processes, associated with different materials.

AeroSup operates in a global SC. Its suppliers are spread worldwide, and it exports 100% of its production to a single customer. In the context of this work, a single product element is considered. It is a large reference panel whose dimensions are 18 m (length) x 5 m (width) and is used in the most significant products supplied by AeroSup. The processes and materials which are being considered as an alternative to the autoclave are still at a very preliminary, laboratory stage, and are not yet implemented in the real manufacturing system at AeroSup. Hence, the processes are not yet scaled-up to an industrial level. For this case study, the laboratory conditions have been reported elsewhere (Santos 2017), and a linear scale-up has been considered for the industrial conditions, using a conversion factor of 2,35, following the current industrial conditions referred in Marques (2018). At this stage it is expected that the industrialization process can be a very long and demanding process, given the industry quality standards. This preliminary sustainability performance assessment is critical for two reasons. First, gaining an early insight into the impact of uncertainties in the SC; second, acquiring early information about possible sustainability gains as a consequence of the use of other composites curing technologies.

From an industrial perspective, composite materials have been used in the aircraft industry to address sustainability challenges (Solvay 2017). There are several processes that allow the manufacture of carbon-fiber materials (Advani and Hsiao 2012) and are generally grouped according to the curing process. In the curing process the materials are divided into those that are produced by autoclave, the most common in the aerospace industry (Liu et al. 2018), and those that are produced out-of-autoclave (OoA).

In this demanding context three manufacturing processes will be studied: one bag molding, cured in an autoclave, and two that are cured OoA, including vacuum assisted resin injection (VARI) and vacuum-bag-only (VBO) processes. Processes like VARI and VBO offer improvements in the environmental performance and other areas like productivity, quality, and in social questions as the employee retention (Schwartz 2011). The bag molding and VBO processes use prepregs materials, needing a cold-chain logistics and a temperature-controlled room storage.

4.2. Critical performance indicators

The tardiness of the products will be measured as a penalty cost imposed by the customer for orders arriving late, the resources utilization will be assessed through the analysis of the occupied production capacity in different simulation periods, and the inventories measured by the average levels of materials in stock at the manufacturer. The list of orders will be studied for better understanding the capacity to recover from disturbances at the manufacturer.

Though the GRI guidelines have been considered as the basis for the selection of the critical performance indicators, not all the GRI(2013) indicators have been included in the analysis. The sustainability indicators result from the intersection of three major sources of information: data availability in the model application case, the benchmark of metrics in industrial sustainability reports, and GRI indicators. The selected aspects for the performance indicators, the performance indicators, and the detailed description of the contents considered for each Indicator are presented in Table 2. The selected performance indicators are not a one-to-one match with the aspects and indicators specified by the GRI.

The social indicators were the most difficult to select. Hence, we considered the work by Popovic et al. (2018), and selected a quantitative indicator in the social category, and employment aspect, which was possible to assess given the data available for the case study, the working hours.

All indicators should be analyzed in combination and not in isolation. Therefore, and following the work by Rabelo et al. (2007), an MCDA is applied, that helps ranking the performance of the different manufacturing processes, according to different interests.

Table 2. Selected sustainability performance indicators divided by the three sustainability pillars (categories) – economic, environmental, and social –, some indicators aspects as in the GRI, indicators, and description of the contents for each indicator

Categories	Aspects	Performance Indicators	Acronym	Description
Economic	Economic performance	The direct economic value generated and distributed at the manufacturer	DEVGD	Operating costs – machines running costs, material costs, tools costs, initial investment costs, and transport costs, measured in mu. Employee wages and benefits - costs associated with the human resources working hours, measured in mu.
Environmental	Energy	Energy consumption within the organization	ECWO	Energy consumption of the production process, measured in kWh
		Energy consumption outside the organization	ECOO	Energy consumption of the production process at the suppliers, measured in kWh
	Emissions	Direct GHG emissions	DGHGE	CO_2 emissions from the production processes at the manufacturer and suppliers, measured in $kgCO_2eq$
	Transport	Significant environmental impacts of transporting products and other goods and materials for the organization’s operations	SEW	CO_2 emissions from the product and materials transport activities, measured in $kgCO_2eq$
Social	Employment	Working hours	WH	The ratio between the average number of working hours and the working hours regulated by law, measured in dimensionless units

4.3. Model validation and verification

Given its multi-method modelling capability, the Anylogic software has been used. The model validation and verification are a significant part of the process of developing simulation models. The first consists in assessing if the computer program and its implementation are correct (Sargent 2013); it is the model debugging (Kleijnen 1995). The second consists in assessing if the model, within its domain application, originates satisfactory results (Sargent 2013). For verification purposes, the implemented model has been subject to major revisions to assess its resemblance with the data flow diagram in Figure 1, and has been debugged to ensure that there were no codding errors. For validation, some techniques proposed by (Sargent 2011; Sargent 2013) have been used, including extreme condition test, face validity (by enquiring individuals knowledgeable about the system if the model assumptions were reasonable), internal validity, operational graphics, parameter variability, structured walkthrough, and trace. For each scenario, a total of 8 model replications has been run, as determined by the confidence interval method (Robinson 2004), for a 98% confidence interval.

4.4. Experimental design – modelling conditions and scenarios

Based on the work by Özbayrak, Papadopoulou, and Akgun (2007), the scenarios considered in this work encompass the mentioned sources of uncertainty in the MTO SC and have been used as the basis for building the scenarios in the experimental design. The three experimental factors are the demand, the production process, and the supplier lead time. A total of four scenarios is considered, and the model is simulated for a 5-year time horizon:

- Scenario 1 – *the base case*: The SC is simulated under normal and more or less steady conditions, in which there are no disruptions in production, the lead time with the suppliers is known, and demand is stable (though given by a uniform discrete distribution) over the simulation period. The supplier lead time is fixed.
- Scenario 2 – *increase in demand*: There is a sudden increase in demand for the third year of simulation, with the supplier lead time remaining predictable and fixed.
- Scenario 3 – *decrease in demand*: Similar to scenario 2, but demand drops in the third year of simulation.
- Scenario 4 – *supply disruption*: The demand is the same as in the base case, however the supplier does not supply materials for a semester during the third year of simulation.

4.5. Input data

All the input data has been collected in experimental/laboratory conditions Santos (2017) and a linear scale-up has been considered (Marques 2018) to assess conditions which are closer to a real SC. This has an impact in the implications for the industry that can be withdrawn from the model results.

Relevant information for the model includes processing times at the manufacturer, supplier lead times, the costs of the resources used in production, and the CO2 emissions of the transport resources and manufacturing processes. The dataset used for the manufacturer variables is presented in Appendix B, the dataset used for the suppliers in Appendix C, and transport data in Appendix D. Table 3 summarizes the variables considered for each scenario under analysis.

Table 3. Variables used for each scenario under analysis

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**
Customer demand	Uniform discrete (80, 100)	Uniform discrete (80, 100), except in year 3, becoming Uniform discrete (120, 150)	Uniform discrete (80, 100), except in year 3, becoming Uniform discrete (50, 60)	Uniform discrete (80, 100)
Supplier lead time	16 weeks	16 weeks	16 weeks	16 weeks except in the first semester of year 3, in which it does not supply
Manufacturing processes	Autoclave, VARI, VBO	Autoclave, VARI, VBO	Autoclave, VARI, VBO	Autoclave, VARI, VBO

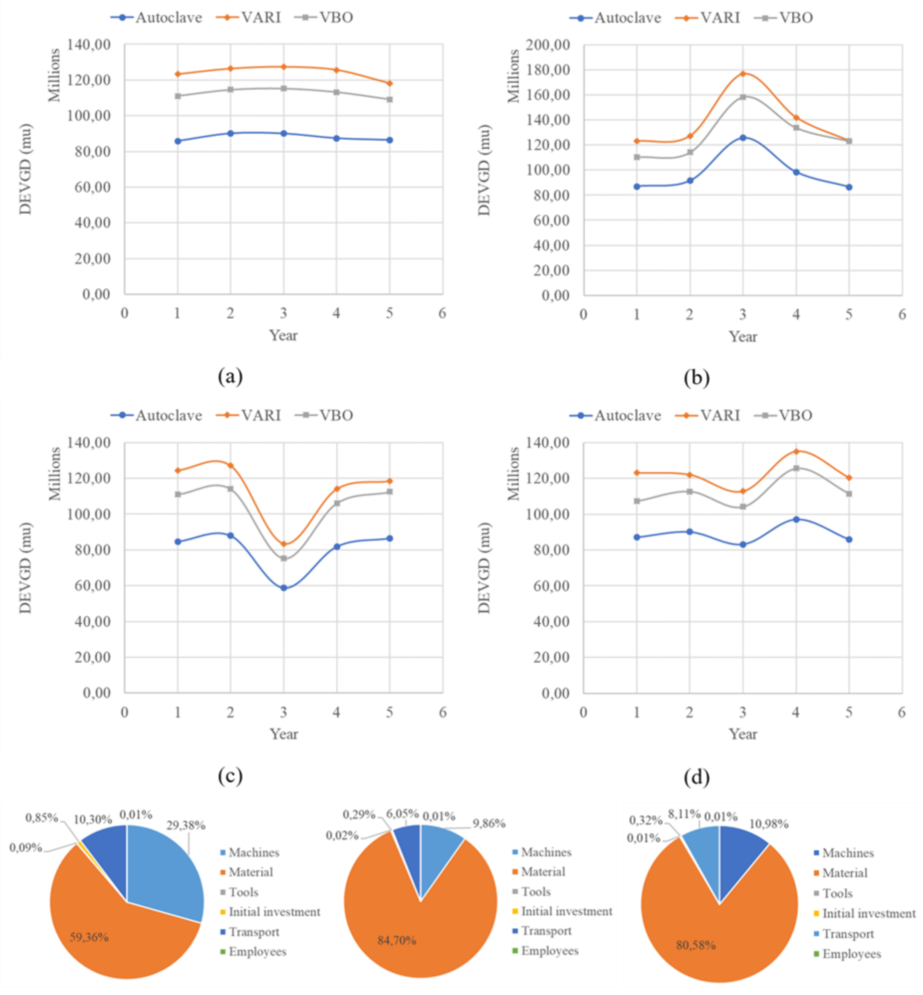
5. Results and discussion

5.1. Economic category

Figure 4 shows the results obtained in the economic category of sustainability, for the DEVGD indicator. Results have been retrieved for the different scenarios considered and show the differences in the costs for the manufacturing processes throughout the simulation years and the distribution of the costs through its categories. The VARI generates the higher costs across all scenarios, Figure 4(a)-(d), while the autoclave is associated to lower costs. The higher costs of the VARI are a consequence of the materials' costs. As Figure 4(f) shows, materials are responsible for 84,70% of the total costs, while the manufacturing process itself is responsible for 9,86% of the total costs. All costs of the VARI are lower than those of the autoclave, except for the materials and the costs with the workforce (employees). This indicates the potential of the VARI in achieving lower manufacturing costs, and the need to establish contracts with suppliers to lower the costs with the acquisition of the materials or engaging the in the development of new and more affordable materials. For the autoclave, the costs of the process, the machines working costs, are 29,38% of the total costs, which corresponds to more than twice the machine working costs for the VARI and VBO.

In the base case scenario, Figure 4(a), the costs remain approximately constant throughout the simulation years, with small variations due to the differences in the demand. When the demand increases in the third year of simulation, Figure 4(b), the costs increase 38% when compared to the base case, and for the VBO, there is no recovery of the cost to its base value. In the fifth year of simulation, the VBO DEVGD becomes similar to that of the VARI process. This is because the VBO, given its lower scaled-up capacity, cannot recover from the increase in demand as fast as the VARI and autoclave processes. For this, more units are manufactured in the fifth year of simulation for the VBO, increasing the DEVGD indicator.

When the product demand decreases in the third year of simulation, Figure 4(c), there is a general decrease of 34% in the DEVGD indicator for all manufacturing processes. This decrease is related to the lower manufacturing demands due to the decreased demand during that period. When the supplier is the disruptive factor in the SC, as in scenario 4, Figure 4(d), there is an initial decrease in the DEVGD in year 3, followed by its increase in year 4. This occurs because there are no costs associated with the acquisition of the materials for manufacturing during the second semester of the third year of simulation. When the supplier restarts the material supply at the beginning of the fourth simulation year, the orders which are in the suppliers' orders' list are shipped and the manufacturer incurs in costs associated with the acquisition of those materials which are late. Additionally, as the manufacturing activities have been lowered due to the absence of the needed materials, the manufacturer must respond to an increased orders' list, with an increased manufacturing activity.



(a) (b)

(c) (d)

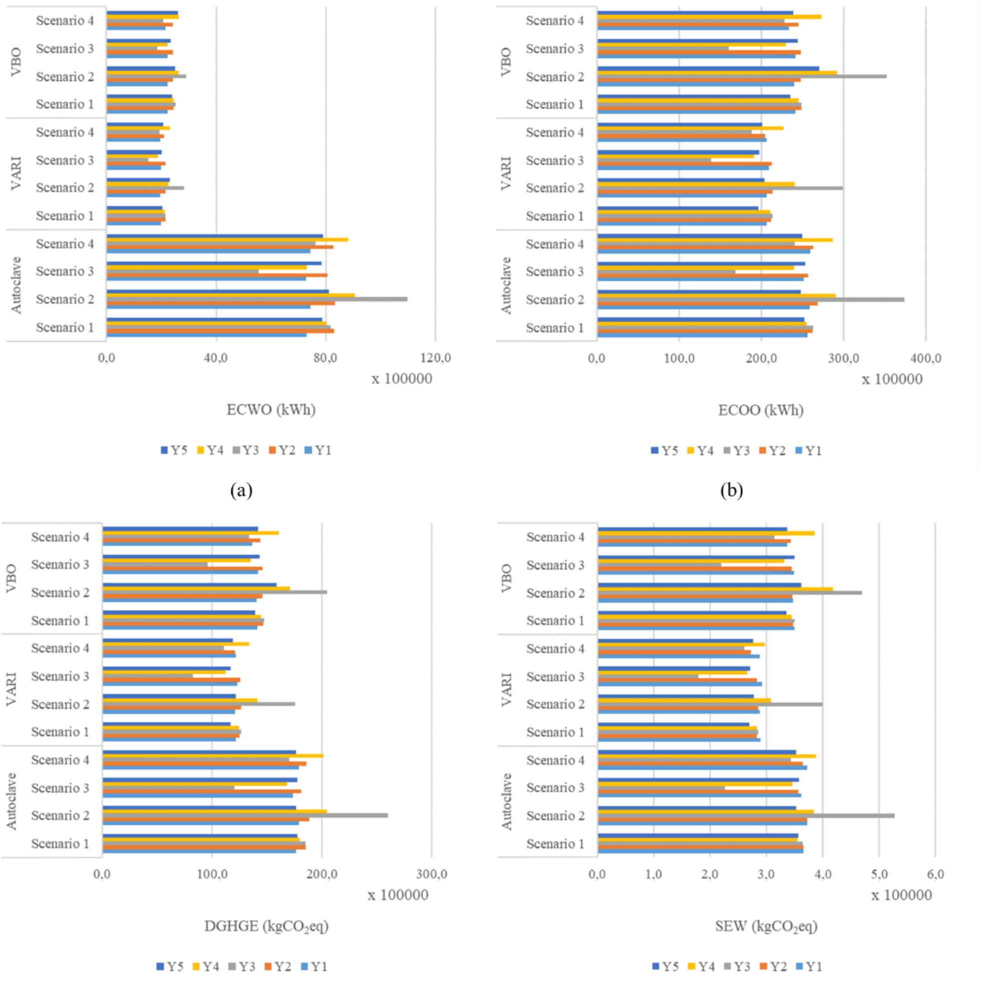
(e) (f) (g)

Figure 4. DEVG and distribution of costs for the four scenarios, and for each manufacturing process. (a) Scenario 1; (b) Scenario 2; (c) Scenario 3; (d) Scenario 4. (e) Distribution of costs for the autoclave. (f) Distribution of costs for the VARI. (g) Distribution of costs for the VBO.

5.2. Environmental category

The results obtained for the environmental category of sustainability are presented in the graphics from Figure 5. In Figure 5 (a) major differences are verified for ECWO indicator across the manufacturing processes. In the autoclave, the energy consumption can be nearly four times higher than for the VARI and VBO. When comparing the scenarios, an increase in the energy consumption is verified in the third year of simulation for scenario 2, a decrease in the energy consumption in the third year for scenario 3 and smaller increase in the energy consumption in the fourth year of simulation in scenario 4. The increase and decrease in energy consumption in the year 3 for the scenarios 2 and 3 are induced by the increase in demand, and decrease in demand, respectively. A higher demand entails consumption of more resources, as the manufacturing processes must occur more times. The opposite is verified when there is a decrease in demand. In scenario 4, though the SC disturbance occurs in the third year, the variation in the energy consumption occurs in the fourth year, when the manufacturer receives the materials late, and must respond to demand that should have been fulfilled in year 3.

In what concerns to the ECOO indicator, represented in Figure 5(b), lower energy consumption on the suppliers' side, for obtaining the materials to be used in manufacturing, is verified for the VARI. The materials used in this process are known for a lower environmental impact, than those prepregs used for the autoclave and VBO. The variations across the scenarios have an interpretation which is similar to that of the ECWO indicator.



(a) (b) (c) (d)

Figure 5. Environmental performance category indicators for each scenario analysed. (a) ECWO; (b) ECOO; (c) DGHGE; (d) SEW.

The DGHGE indicator, represented in Figure 5(c) contains the CO_2 emissions originated from the manufacturer and supplier activities. It is possible to rank the manufacturing processes in crescent order of emissions in the following sequence: VARI, VBO, and autoclave. This represents a great advantage of the VARI process for environmental purposes. For the CO_2 emissions from the transport activities in Figure 5(d), lower emissions are obtained in the VARI process. On one hand, the transport of the materials from the supplier to the manufacturer does not require the use of a refrigerated truck, which is associated to higher CO_2 emissions and, on the other hand, the final product obtained through the VARI is associated with a lower weight, resulting in lower emissions with the transport of the final product.

5.3. Social category

In the social category, the indicator analyzed was the WH. It reflects two features of the manufacturing technologies that have direct impact in the worker. First, if the working hours are within the limits established by law – when it exceeds the unit, the number of hours worked have exceeded the legally imposed limits. Second, it represents the potential of the manufacturing technology in generating work positions, as a higher WH is associated with higher number of direct working hours and may indicate the need to hire more workers. The results of the WH indicator are presented in **Erro! A origem da referência não foi encontrada.**.

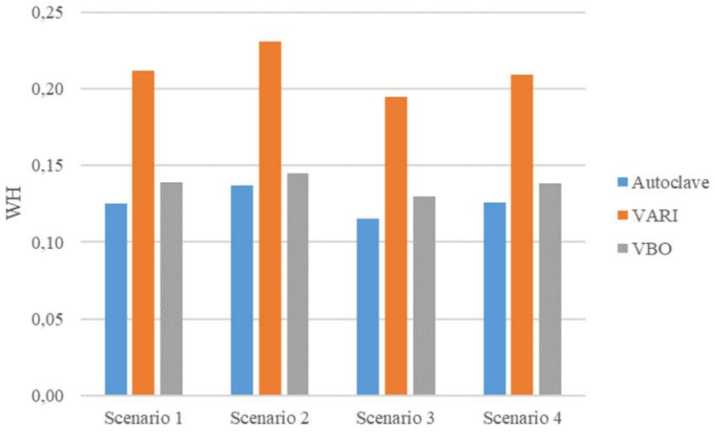


Figure 6. Social category indicator WH obtained for the different scenarios and manufacturing processes.

From **Erro! A origem da referência não foi encontrada.** shows that none of the technologies present a WH which exceeds the unit and, for this, the law working limit hours is respected across all scenarios. Notwithstanding this, the WH indicator is sensitive to the variations in demand, as the results from scenarios 2 and 3 show. An increase in demand throughout the simulation years increases the WH indicator, while a decrease in the demand decreases the WH indicator. This occurs because the number of units to be produced, and the manufacturing hours associated with that production, vary according to the demand. A supplier disruption, as in scenario 4, did not generate impact in the WH indicator, because the sum of manufactured units across the simulation years was the same. The VARI presents a WH higher than for the remaining processes, across all scenarios. This shows that a higher number of employee working hours are required for this process. Hence, it has the potential to generate more employment opportunities. Despite the value of the WH indicator, the working conditions (e.g. safety, exposure to dangerous chemicals) should also be evaluated, which is missing in this analysis.

5.4. Other indicators

As referred in sub-section 4.2, other indicators important to evaluate in MTO SCs are the tardiness in deliveries, resource utilization, inventory levels, and the order list. The results for these indicators are presented in Figure 7. The tardiness has been measured as a penalty cost imposed by the customers for receiving late deliveries, the utilization of the resources is represented as a percentage of the installed capacity that has been used, the inventory levels are given by the average weight of the materials in stock at the manufacturer and the orders' list represent the average monthly number of reference panels waiting to be manufactured/delivered in each simulation year.

The simulation results in Figure 7(a) show that the in scenarios 1 and 3, none of the manufacturing processes incurs in tardiness costs, while in scenario 4, all manufacturing processes incur in these costs. In scenario 2, results are mixed, with the VARI and VBO presenting tardiness costs in year 3, and years 3 and 4, respectively. The autoclave registered null tardiness costs in scenario 2. In scenario 2, the tardiness costs for the VARI and VBO can be associated with the utilization levels, Figure 7(b), reaching near 100%; in scenario 4, the tardiness costs are related to the absence of materials to proceed with the manufacturing activities. The utilization levels are closely related to the installed manufacturing capacity. For the scale-up of the manufacturing activities considered in the context of this work, the process with the lower installed capacity is the VBO. If this is confirmed in practice, major concerns may arise from the utilization of this process during periods of higher demand. The autoclave is the one with lower utilization among the three processes. Though this has a better capacity to absorb sudden increases in demand, much of the installed capacity remains unused in the scenarios analysed.

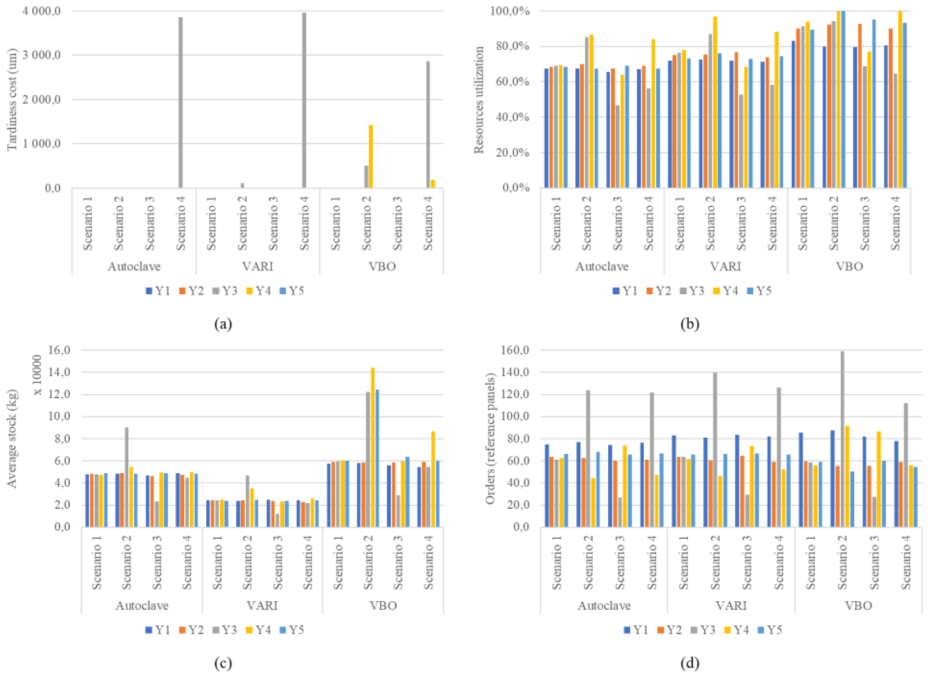


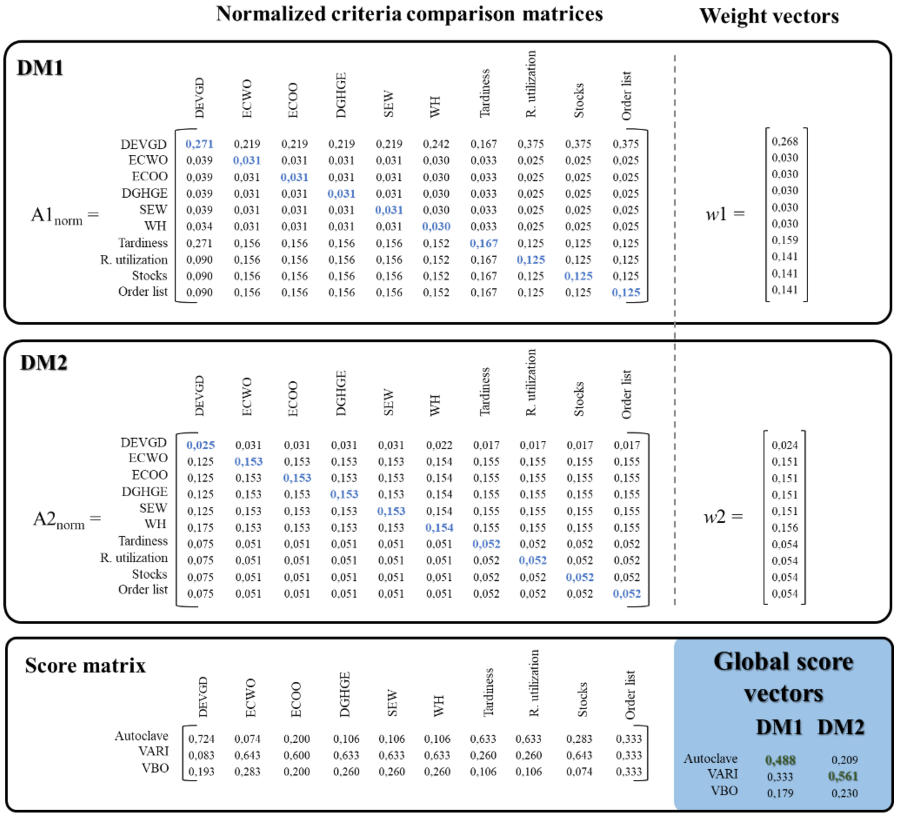
Figure 7. Other relevant performance indicators for the MTO SCs. (a) Tardiness; (b) Resources utilization; (c) Average materials stock; (d) Order list.

In Figure 7(c), the average stock of materials presents its higher values for the VBO, and the lower values for the VARI. The orders' lists are similar among the manufacturing processes, as Figure 7(d) shows, though a remarkable increase in this list is verified in scenarios 2 and 4 in the third year of simulation. These are associated with the increase in demand and to the inability of the supplier in providing the needed materials for manufacturing.

5.5. Overall recommendations – assessment through AHP

In this section, the results of the implementation of the AHP considering different criteria and manufacturing processes are presented. In our approach, there was no inquiry to experts of the system, but a consideration of DMs with different profiles and priorities. Two types of DMs have been considered. fDM1, values a lower DEVGD indicator alongside the tardiness, lower resource utilization, lower stocks, and lower orders' list. DM2, is driven by the environmental and social categories of sustainability. The normalized comparison matrices, the weight vectors and the score matrices for the two DMs are presented in Figure 8. The global score vectors show that maintaining the autoclave would be the choice for DM1, while for DM2, changing the manufacturing process to the VARI would be the final decision. These are two illustrative examples of the decisions that can arise from the analysis of the simulation model results. Other DMs' profiles could be analyzed, or decision-making processes considering the views from more than one decision-maker.

This type of MCDA is extremely relevant in the context of this work, especially as no manufacturing process outperforms the remaining in all analyzed performance indicators, which is likely to introduce more uncertainty during the decision-making process. This approach would acquire a more valuable contribution if it could would consider real decision-makers, with conflicting opinions and profiles.



Normalized criteria comparison matrices

Weight vectors

DM1

$A1_{norm} =$

	DEVGD	ECWO	ECOO	DGHGE	SEW	WH	Tardiness	R. utilization	Stocks	Order list
DEVGD	0,271	0,219	0,219	0,219	0,219	0,242	0,167	0,375	0,375	0,375
ECWO	0,039	0,031	0,031	0,031	0,031	0,030	0,033	0,025	0,025	0,025
ECOO	0,039	0,031	0,031	0,031	0,031	0,030	0,033	0,025	0,025	0,025
DGHGE	0,039	0,031	0,031	0,031	0,031	0,030	0,033	0,025	0,025	0,025
SEW	0,039	0,031	0,031	0,031	0,031	0,030	0,033	0,025	0,025	0,025
WH	0,034	0,031	0,031	0,031	0,031	0,030	0,033	0,025	0,025	0,025
Tardiness	0,271	0,156	0,156	0,156	0,156	0,152	0,167	0,125	0,125	0,125
R. utilization	0,090	0,156	0,156	0,156	0,156	0,152	0,167	0,125	0,125	0,125
Stocks	0,090	0,156	0,156	0,156	0,156	0,152	0,167	0,125	0,125	0,125
Order list	0,090	0,156	0,156	0,156	0,156	0,152	0,167	0,125	0,125	0,125

$w1 =$

0,268
0,030
0,030
0,030
0,030
0,030
0,159
0,141
0,141
0,141

DM2

$A2_{norm} =$

	DEVGD	ECWO	ECOO	DGHGE	SEW	WH	Tardiness	R. utilization	Stocks	Order list
DEVGD	0,025	0,031	0,031	0,031	0,031	0,022	0,017	0,017	0,017	0,017
ECWO	0,125	0,153	0,153	0,153	0,153	0,154	0,155	0,155	0,155	0,155
ECOO	0,125	0,153	0,153	0,153	0,153	0,154	0,155	0,155	0,155	0,155
DGHGE	0,125	0,153	0,153	0,153	0,153	0,154	0,155	0,155	0,155	0,155
SEW	0,125	0,153	0,153	0,153	0,153	0,154	0,155	0,155	0,155	0,155
WH	0,175	0,153	0,153	0,153	0,153	0,154	0,155	0,155	0,155	0,155
Tardiness	0,075	0,051	0,051	0,051	0,051	0,051	0,052	0,052	0,052	0,052
R. utilization	0,075	0,051	0,051	0,051	0,051	0,051	0,052	0,052	0,052	0,052
Stocks	0,075	0,051	0,051	0,051	0,051	0,051	0,052	0,052	0,052	0,052
Order list	0,075	0,051	0,051	0,051	0,051	0,051	0,052	0,052	0,052	0,052

$w2 =$

0,024
0,151
0,151
0,151
0,151
0,156
0,054
0,054
0,054
0,054

Score matrix

	DEVGD	ECWO	ECOO	DGHGE	SEW	WH	Tardiness	R. utilization	Stocks	Order list
Autoclave	0,724	0,074	0,200	0,106	0,106	0,106	0,633	0,633	0,283	0,333
VARI	0,083	0,643	0,600	0,633	0,633	0,633	0,260	0,260	0,643	0,333
VBO	0,193	0,283	0,200	0,260	0,260	0,260	0,106	0,106	0,074	0,333

Global score vectors

	DM1	**DM2**
Autoclave	**0,488**	0,209
VARI	0,333	**0,561**
VBO	0,179	0,230

Figure 8. AHP results for the two DMs considered.

5.6. Managerial insights

The results from the hybrid model show that none of the manufacturing processes analyzed outperforms the others in all the dimensions of performance. While the autoclave is the most economically viable process, the one with the lowest tardiness and utilization of resources, the VARI is the one that achieves the highest environmental and social gains, and the lower stocks. As the autoclave is the most technologically mature process among those studied, future technological improvements and evolution of the VARI and VBO may significantly alter these results. Despite the analysis of the results in this work being constrained by a linear process scale-up, important conclusions can be retrieved.

- The VBO is the least attractive process alternative, as it is not the best alternative in at least one of the performance indicators considered;

- An opportunity for improving the environmental and social sustainability dimensions exist, if the VARI is adopted, though with higher cost. This could be overcome by establishing long-term relationships with suppliers, given the high costs with the acquisition of materials. Also, while the process matures, significant alterations to this reality can exist and it can become more cost-competitive;

- The social sustainability indicator must be refined, so that it becomes possible to reflect in the WH, the effect of the working conditions of the employees.

Conclusions and future research directions

This work contributes to answering the initial research question proposed, How to include a sustainability-oriented perspective on the operational performance assessment of MTO SCs?, in a number of ways. First, it proposes a hybrid MTO SC simulation model for performance assessment, that uses SD, DES, and ABS to tackle the diverse requirements of modelling the MTO SC activities. Data from a real laboratory case study has been used, which has been linearly scaled-up to test the model under an industrial context. Additionally, AHP has been used to understand differences in the decision-making process outcomes for DMs with different profiles. Theoretical and managerial contributions can be retrieved from this work, as well as important opportunities for improvement.

From a theoretical perspective, multiple fields of knowledge have been integrated in this work, including simulation, MCDA, SC sustainability, and performance assessment. Each included topic was of equal relevance to the overall goal of the work. While the simulation model contributes to the hybrid simulation literature, showing that hybrid simulation approaches can become a great value added; its focus on the sustainability of MTO SCs contributes to the sustainability performance assessment literature. Such model allows modelling complex SCs with different levels of detail and without incurring in an improper use of the simulation methods and constitutes an addition to previously published models focusing on other customer-oriented SCs. The use of simulation for performance assessment provides the opportunity to integrate a dynamic analysis of this topic and considering many stochastic variables which have a direct relation to real world.

From a managerial perspective, the outcomes of the performance assessment are much dependent on the profiles of the DMs. An informed a decision does not only depend on the analysis herein presented. We should highlight the fact that the aerospace industry is very regulated and has very high-quality standards. Hence, only if the manufacturing processes prove to produce parts with the required quality, these could be approved. The conclusions derived from this work have limited value as the model is very sensitive to the input data, and this data has been linearly scaled-up from laboratory conditions. This linear scale-up is probably far from being a good scale-up for all the processes and all the process variables but is herein considered as a starting point.

This work presents countless opportunities for improvement. From the model perspective, learning curves could be included in the SD model to address the time productivity variation of the workers. Also, the SD model could be complemented or substituted by a more detailed DES model. Hence, a balanced tradeoff between the available information about the system and the model detail should be well thought out. For the model experimentation, additional case studies should be considered, and for the current case study, other scale-up alternatives evaluated. Additionally, other indicators should be assessed, and the selected indicators explored in higher detail.

For the hybrid model building process, future work should include the development of a common and formal framework for the MTO supply chains, with an explicit guide with the key manufacturing activities to be included, the segmentation of the MTO SC, a roadmap for the selection of the simulation methods, and where key tradeoffs must be established during the modelling and simulation exercise.

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Appendix A – SD model equations

This appendix presents the equations used for the SD policy structure of inventory and production model presented in Figure 3.

Table A. 1. SD model equations

Name	Type	Description	Equation	Units
Finished Products	Stock	Stock of finished products ready for delivery	INTEGRAL (Finishing rate, 0)	Product
Processed Products	Stock	Stock of products being processed	INTEGRAL (Process rate – Finishing rate, 0)	Product
Raw Materials Stock	Stock	Stock of raw materials to be used in the manufacturing process	INTEGRAL (- RM use rate, initial raw materials stock)	Material
WIP	Stock	Stock of products ready to start the manufacturing process	INTEGRAL (Production start rate – Process rate)	Product
Finishing rate	Rate	Rate at which the products start finishing activities	IF THEN ELSE (Processed Products>0, 1/finishing time, 0)	Product/time
Obsolescence rate	Rate	Rate at which materials become obsolete given their shelf life	Raw Materials Stock/shelf life	Material/time
Process rate	Rate	Rate at which the products start manufacturing	IF THEN ELSE (WIP>0, process capacity / process time, 0)	Product/time
Production start rate	Rate	Rate at which the process setup/preparation occurs	MAX (0, MIN (desired start rate, MIN (feasible production start from materials, setup capacity / setup time)))	Product/time
RM use rate	Rate	Rate at which the materials/components are used in the production process	Production start rate * material use per product * (1+percentage of process waste)	Material/time
adjustment time	Parameter	Time to adjust the WIP levels	-	time
desired production start rate	Parameter	Rate at which production must start to respond to the demand	-	Product/time
finishing time	Parameter	Time necessary for the finishing activities of one product unit	-	time/Product
inventory coverage	Parameter	Coverage of expected demand	-	time
material use per product	Parameter	Number of materials/components used in one product unit	-	Material/Product
process capacity	Parameter	Number of products that can be simultaneously manufactured	-	Product
process time	Parameter	Duration of the manufacturing process	-	time
percentage of process waste	Parameter	Percentage of materials wasted during manufacturing	-	dimensionless
setup capacity	Parameter	Number of products that can be simultaneously prepared for manufacturing	-	Product
setup time	Parameter	Time for the setup/manufacturing preparation	-	time
shelf life	Parameter	Shelf life of the materials used in production	-	time
desired material use rate	Variable	Desired use rate of materials/components considering the product demand	desired production start rate * material use per product	Material/time
desired start rate	Variable	Desired production start rate adjusted to keep the WIP in desired levels	WIP adjustment + desired production start rate	Product/time
desired WIP	Variable	Level of WIP that produces the desired rate of production, considering the manufacturing process time and the process capacity	MIN (desired production start rate*process time, process capacity)	Product
feasible material use rate	Variable	Possible material use rate, considering the maximum possible material use rate and the desired material use rate	MIN (maximum material use rate, desired material use rate)	Material/time
feasible production start from materials	Variable	Possible production start rate based on the materials/components stock constraints	feasible material use rate / material use per product	Product/time
maximum material use rate	Variable	Maximum materials/components use rate, considering the stock levels and the inventory coverage	Raw Materials Stock / inventory coverage	Material/time
WIP adjustment	Variable	Modification to production starts to keep the WIP in the desired level	(desired WIP - WIP) / adjustment time	Product/time

Appendix B – Manufacturer data

The manufacturer, being the most complex agent considered in the simulation is also that which presents higher data requirements. Information required for the model run includes the costs of the resources used in production, the production preparation, production and finishing times, the number of resources involved in production, the amount of material used for each reference panel, environmental information, and the initial investment and tooling costs. When production finishes, the final reference panels are transported in batches of four units. Tables B.1 – B.5 present the input data used for the manufacturer.

Table B. 1. Production resources costs

Resource	Labour	Autoclave	Oven	Vacuum	Lay-up machine
Cost	29.5	3671.1	1048.9	262.2	2425.6
Unit	mu/hour	mu/hour	mu/hour	mu/hour	mu/hour

Table B. 2. Materials and product information

Manufacturing process	**Materials used**	**Material use per product (kg)**	**Initial raw materials stock (kg)**	**Material shelf life (months)**	**Final product weight (kg)**
Autoclave	M1	739.4	73940.0	12	568.8
VARI	M2	485.9	48590	12	542
	M3	218.2	21820	12	
VBO	M4	716.0	71600	18	550.8

Table B. 3. Manufacturing process information

Manufacturing process	**Initial setup time (hours)**					**Process time**				**Finishing time**			**Process preparation (parallel machines with unit capacity)**	**Process capacity (manufactured units/machine)**	**Number of process machines**	**Number of lay-up machines**	**Tooling replacement cycle (manufactured units)**	**Process waste (%)**
	Total	**Lay-up machine**	**Oven**	**Vacuum**	**Labour**	**Total**	**Autoclave**	**Oven**	**Vacuum**	**Total**	**Automated**	**Manual**						
Autoclave	1.61	1.13	0.00	0	0.48	12.00	12.00	0.00	12.00	0.27	0.19	0.08	1	1	1	1	1000	30
VARI	5.88	2.02	1.13	1.87	0.87	13.06	0.00	11.55	11.08	0.27	0.19	0.08	1	1	1	1	500	30
VBO	3.71	1.29	0.00	1.87	0.55	15.94	0.00	15.94	15.94	0.27	0.19	0.08	1	1	1	1	5000	30

Table B. 4. Environmental information per process run

Manufacturing process	**Process preparation CO_2 emissions ($kgCO_2eq$)**	**Process preparation energy use (kWh)**	**Process CO_2 emissions ($kgCO_2eq$)**	**Process energy use (kWh)**	**Finishing process CO_2 emissions ($kgCO_2eq$)**	**Finishing process energy use (kWh)**
Autoclave	241.39	449.51	8018.91	14932.80	40.59	75.58
VARI	605.53	1127.61	1587.14	2955.57	40.59	75.58
VBO	320.15	596.19	2205.86	4107.74	40.59	75.58

Table B. 5. Initial investment costs in machines and tooling cost

Manufacturing process	Autoclave	VARI	VBO
Initial investment cost (mu)	3711414	1778952	1778952
Tooling cost (mu)	170302.32	34100.82	34100.82

Appendix C – Supplier data

At the supplier agent level, the key information used as input for the model includes information about the supplied materials for each supplier, the supplier lead time, the cost of the materials, and the MOQ, as in Table C. 1. Additionally, information about the environmental impact of the production of the supplied materials and the transport information respectively in Table C. 2 and in Table C. 3, is also needed for the model run.

Table C. 1. Supplied materials per supplier, materials lead time, size of the rolls transported, cost of the materials, and MOQ

Supplier	**Supplied materials**	**Lead time (weeks)**	**Roll size (m2)**	**Cost (mu/m2)**	**MOQ (rolls)**
S1	M1	16	190	40.50	1
	M2	16	100	39.86	1
	M4	16	100	76.41	1
S2	M3	16	46	66.70	1

Table C. 2. Environmental information per roll of material

	M1	**M2**	**M3**	**M4**
CO_2 emissions ($kgCO_2eq$)	2038.93	406.5	494.72	1105.66
Energy use (kWh)	3796.89	756.98	921.26	2058.96

Table C. 3. Transport information for each material

Material	**Transport type**	**Transport capacity (pallets)**	**Pallet capacity (rolls)**	**Weight per pallet with maximum roll capacity(kg/pallet)**	**Pallet unit cost (mu)**
M1	Refrigerated truck	10	9	475.33	720
M2	Regular truck	10	9	85.75	0
M3	Regular truck	10	9	392.77	0
M4	Refrigerated truck	10	9	257.76	747.29

Appendix D – Transport data

The transport data that has been used for the model includes the CO_2 emissions, measured in $kgCO_2eq/(km.kg)$ for each transport type, and the transport variable cost, measured in mu/km. These are presented in Table D. 1. The transport variable cost is merely indicative, to reflect differences between the transport types, specifically it is considered that sea transport is cheaper than road transport, and that among the road transport types, the refrigerated truck has a higher variable cost.

Table D. 1. CO_2 emissions, measured in $kgCO_2eq/(km.kg)$ for each transport type

	Transport type		
	Refrigerated truck	Regular truck	Ship
CO_2 emissions ($kgCO_2eq/(km.kg)$)	0.000373651	0.00021619	0.000021619
Variable cost (mu/km)	0.002714	0.001357	0.001086

Paper A1

Operations strategy frameworks in manufacturing, services and product-service systems

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Abstract - Many definitions for operations strategy appear in literature. Yet, after analysing some of these important definitions, there were some common denominators: planning and decision-making. It is through correct operations strategy planning and decisions that organizations achieve competitive edge, and for this reason, the subject is of major importance. In this paper we present a review on operations strategy (OS) in manufacturing, services and product-service organizations. Through the literature analysis we found several differences and fewer similarities between OS in manufacturing and services and also the positioning of product-service systems (PSS) OS, comparing to OS in manufacturing and in services. Our foremost contribution is providing a literature review and an analysis on the content of the OS frameworks.

Keywords - framework; manufacturing; operations strategy; product-service systems; services

I. Introduction

Skinner [1] introduced for the first time the concept of an operations strategy (OS). Since then, several definitions for OS appeared in literature. A few examples include the definition by Lowson (2001) [2], Slack and Lewis [3], Van Mieghem [4], or Reid and Sanders [5]. Despite being different, all share common characteristics. There is always the conversion of objectives into action plans, a decision pattern involved in the concept, and all the decisions are medium to long term. Briefly, the purpose of OS is that organizations properly use their competencies, processes and resources to achieve a strong competitive advantage [6], and successfully create value for customers and stakeholders [7]. However, considering Porter’s work [8], Enders et al. [9] agree that creating superior value for customers is not sufficient to insure profits; the company must succeed in capturing value. Strategy should be a nonstop learning process as markets are now global and their settings are always changing. It is crucial to have skills to learn to cope with changes [10, 11] and even revise the first strategic plan [12]. Thus, all members in an organization have the duty to bind themselves to a continuous learning process and strategy formation [10, 13], being communication a key asset [14]. Constant knowledge building is a competitive advantage [15].

rations management (OM), technology selection, product development, human resources, among others - is affected by OS [16-19]. Given the impact of OS in organizations, some specialize in specific tasks, while others have to be outsourced. This is a means for higher efficiency and cost reduction [20]. It is important that companies tie strategic objectives to operational capabilities, and understand their limits [21, 22].

There are two elements in OS, as stated by Martín-Peña et al. [23]: competitive priorities (CPs) and operations decisions. The first refers to aims the organization pursues and identifies the areas where operations should be outstanding to offer competitive advantage; the second relates to decisions that aid in achieving the operations and corporate goals and can be split into structural and infrastructural. This division was first proposed by Hayes and Wheelwright in 1984 [24].

Van Mieghem [4] proposed a conceptual framework for OS with three crucial components: competencies, resources and processes, as in Fig.1. The framework can build on the market view to define the competencies that operations should develop through proper selection of resources and processes. This refers to a customer driven organization. Indeed, the same framework can be seen from a different perspective, the resource and processes perspective. Here, the resources and products are the strategic building blocks; therefore, it is possible to insure that the value proposition offered to customers will be properly delivered. The second view is resource driven.

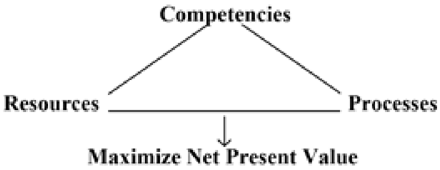

Fig. 1. Operations Strategy Framework (adapted from [4]).

The strategy can also be seen as directed or emergent. The first allows the senior management in an organization to build a correct planning for the organization of the internal resources, considering the external environment, and the stakeholders' demands. The second focuses on developing, organizing and using resources to attain operational excellence, competitive advantage, market share and good performance [25].

There has been evolution in the concept of OS due to change in market demands. The OS appeared to respond to highly variable demands from customers [26, 27]. With variety in the OS implementation, companies are challenged to choose the best methodology. Barnes [28] reviewed practices used in the formation of OS, e.g. interviews, questionnaires, documentation, among others. The author arguments that there is no best alternative when conducting a case study, only a more suitable approach to given settings of the research.

The research presented in this paper covers the topic of OS frameworks. Our study aims to provide an insight on the most important practices in OS in different contexts: manufacturing, services and product service systems (PSS). Therefore, we try to answer two research questions:

RQ1: Is there any difference in OS in manufacturing and services organizations? If so, what distinguishes them?

RQ2: Where does the OS in PSS falls? Does it approach more to the OS in manufacturing, in services, or a blending?

After a thorough literature research in important scientific databases (Scopus, Emerald Insight, Taylor & Francis Online, Science Direct, among others) and focusing on papers published since the year 2000, we selected 38 papers addressing and focusing on OS issues in the context of manufacturing, services or PSS environments. In our analysis, we focus on the list of journals presented in Table I.

To the best of the author's knowledge there is no literature review covering OS in manufacturing, services and PSS. Our foremost contribution is filling this gap in the literature.

The paper is organized as follows. Section II provides an overview on the most important CPs, focusing both on classical CPs and new trends. Section III stresses the implementation of OS in manufacturing companies, whilst Section IV focuses on the implementation of OS in purified service companies and Section V refers to the application of OS in PSS. Section VI provides an analysis on the proposed research questions and an analysis on the revised literature. We conclude the paper with a summary on the main findings of this research work.

II. Competitive Priorities and Operations Strategy

CPs and OS are closely linked [11]. CPs are a set of known goals for OS [29, 30]. In its turn, business strategy (BS) must be supported by OS decisions [30]. The definition of CPs encourages creating competitive edge for companies [31, 32]. Structural and infrastructural decisions influence the success or failure of organizations, concerning their established CPs [33]. If the objectives of a firm are not clearly translated into an adequate bundle of actions, its performance might not fulfil expectations [34].

CPs are particularly important for organizations due to reduced products life cycle and profits, and augmented delivery requirements and globalized competition [35]. Every company deals with more than one customer and should be able to adapt its OS. High flexibility and variety are, thus, crucial [27].

Cost, quality, flexibility, dependability and delivery are the most common CPs [27, 30, 34]. Others include innovation, environmental protection, social sustainability and customer service or after sales service [23, 32, 36, 37]. The innovation perspective makes the firm more disposed to recognize shifts in market dynamism and also to align its processes according to changes in industry [38, 39]. Environmental protection is supported by environmental programs, as ISO 14001 [40]. Based on this, we propose a division between CPs into classical and recent trends, as Fig. 2 illustrates.

Table 1. List of journals and number of analysed papers in each

Journal	Papers	OS in Manufacturing	OS in Services	OS in PSS
	No. of papers	No. of papers	No. of papers	No. of papers
Computers & Operations Research	1	0	1	0
European Management Journal	1	0	1	0
Industrial Marketing Management	1	0	0	1
International Journal of Industrial Engineering	1	0	1	0
International Journal of Operations & Production Management	7	3	1	3
International Journal of Production Economics	4	2	2	0
International Journal of Production Research	3	3	0	0
International Journal of Service Industry Management	3	0	1	2
Journal of Business & Industrial Marketing	1	0	0	1
Journal of Engineering and Technology Management	1	0	0	1
Journal of Industrial Engineering and Management	1	1	0	0
Journal of Manufacturing Technology Management	5	3	0	2
Journal of Operations Management	4	3	1	0
Journal of Service Management	1	0	0	1
Management Decision	1	0	1	0
Managing Service Quality: An International Journal	1	0	1	0
Procedia Social and Behavioural Sciences	1	0	1	0
Technovation	1	0	0	1
TOTAL	38	15	11	12

Martín-Peña et al. [23] found, that there were three OSs: the first aimed at costs, the second was providing the product to the customer as quickly as possible and on time, with high quality, and the third was related to firms using new technologies and processes, allowing them to adapt to new customer requests. OS must adapt to new technologies and industry growth [39]. It is concluded that operations are designed to meet customers' needs and provide a competitive edge to the organizations.

Classical competitive priorities

- Cost;
- Quality;
- Flexibility;
- Dependability;
- Delivery.

Recent trends in competitive priorities

- Innovation;
- Environmental protection;
- Social Sustainability;
- Customer/after sales service;
- Brand.

Fig. 2. Classical and recent trends in CPs.

The importance given to CPs was not the same throughout time. It has evolved from cost to quality and delivery and flexibility, being nowadays more focused on innovation and customer service [32]. Also, products are not only valued by functionality, but also by the brand [9, 26], that makes a statement about a living style and a positioning in society [26].

Considering the literature in OS and in CPs, we are now in position to summarize concepts in a generic framework. Our framework builds on the directed and emergent strategies concepts [25] and also on the top-down, bottom-up, market view and resources view, as in [3]. In our understanding the top-down perspective is a business needs perspective showing what the organization wants to do and how it is positioned in the market, the business plans. The market view is the market needs that show what the markets require the organization to provide. These two, business needs and market needs are the direct strategy.

Meanwhile, the bottom-up perspective is related to the operations environment and provides knowledge that is built inside an organization, based on the operations experience. The resources view is related to the resources and capabilities owned by the organization, which dictate what the organization can and cannot do. These last perspectives, operations environment and resources and capabilities, are the emergent strategies. These concepts are summarized in Fig.3.

Fig. 3. Summary framework.

III. Operations Strategy in Manufacturing

Manufacturing firms have been implementing different strategies, as just-in-time, agile manufacturing, quick response manufacturing, among others [11].

The fit between process environment and advanced manufacturing technology, and the impact on manufacturing and business performance were studied by Das and Narasimhan [41]. The manufacturing process the company chose was a strategic decision and impacted the overall performance. The proposed framework involved relationships amid process environment, manufacturing technology and performance. It put forward that the process environment configured investments in technology resources, infrastructures and human resources. The ‘ideal profiles’, which matched OS with competitive conditions, aligned the process environment with investments in manufacturing technology. A linkage between performance and technology investments was found.

Silveira [42] tested the use of the order-winners framework from Hill (1985), in 183 organizations from 17 countries. The author tested for a negative connection between performance in business and nonconformity with markets and products, and manufacturing and investments. Internal and external fits were considered. The manufacturing organizations replied to questionnaires and rated the order-winners variables (delivery speed, unique design and cost). The investment in plant and equipment, the production process and the number of days spent in work-in-process inventories were accessed. The business performance of the respondents was evaluated for the domestic market share, the return on investment (ROI) and the return on sales (ROS). Calculating the fit, the author concluded on a negative impact on market share for organizations with nonconformist products with markets and manufacturing and investment. This misfit was not so linked to ROI and ROS.

Using a sample of 353 Spanish manufacturing companies, in [33] were studied both choices and practices involved in operations strategies among manufacturing firms and their effects in the competitiveness of the organizations. To gather data, the researchers sent questionnaires to the firms. The main results showed that the most important structural decisions were related to size and plant capacity, followed by process, technology and environment protection. Among infrastructural decisions, the most important related to quality management, work force and manufacturing planning and control systems. The proper decisions provide a competitive edge to the firms.

In [43], Karlsson and Sköld added a network perspective to understand manufacturing management and strategy. The authors suggested that a framework with horizontal and vertical technologies to recognize the future manufacturing strategy would be beneficial. The horizontal technologies related to the performance characteristics of a product; and the vertical technologies were those integrated in technology disciplines (as in university departments). The horizontal technologies created customer value, using the vertical technologies. In the network perspective, different parts controlled distinct resources and activities without overlap. The network became the management unit, instead of the single organization.

Sarmiento, Knowles and Byrne [44] proposed a method for measuring consensus on manufacturing CPs. The authors proposed including the measurement on the importance of each CP, and a measurement on potential relationships amongst pairs of CPs. This would help understanding the relationships between CPs from the strategic and operational perspectives. It was achieved a measure on the trade-offs amid CPs, which implied that knowledge about compatibility amongst CPs.

The 'plug and play' framework was proposed by Tan and Platts [45], as a tool for assisting managers in the process of building models for operations objectives and their adaptation. The authors stressed the need to provide a modelling tool for managers, that would easily and rapidly allow building a model for manufacturing simulation and analysis. The 'plug and play' framework used four building blocks (cost, quality, flexibility and throughput) that helped developing a manufacturing decision model, analyse connections and prioritising actions.

To examine the influence of BS upon the relationship between OS and business results, Oltra and Flor [30] used a sample of 76 Spanish ceramic tile firms. To represent the OS, the authors used the CPs and the BS following Miles and Snow’s typology (1978). It was suggested that the effect OS had on business performance depended upon the type of strategy followed and, for this, there must be coherence between OS and BS.

A model creating alignment between business and operations strategies was provided by Shavarini, Salimian, Nazemi and Alborzi [22]. A sample of 160 Iranian companies was investigated by means of interviews and closed questionnaires. For the OS, the model considered top-down and resource-based approaches. The framework integrated BS, CPs and the strategies in operational decisions. BS regulated OS and in opposite direction, operational capabilities regulated BS. After data handling, the authors concluded that the alignment differed between companies that achieved success and those that did not, and that different business strategies should be linked to different decisions in OS to seek for success.

Xu, Zhang and Ma [46] introduced a framework for manufacturing OS and tested in 688 Chinese companies. The framework included the relationship among customer demand, enterprise strategy and manufacturing systems functional objectives. Customer demand was assumed to have positive effect on the competitive strategy (operational, financial and strategic); customer demand and competitive strategy were assumed to have a positive effect on the manufacturing systems functional objectives (efficiency, service, environment, time, quality, cost). The results from the questionnaires confirmed that customer demand had a positive effect both on competitive strategy and manufacturing systems functional objective. Also, customer demand had higher influence on the manufacturing systems functional objective than the competitive strategy.

According to Kim, Sting and Loch [19], the process formation of OS is complex and transversal to several layers of an organization. The authors presented a model for OS, based on Kim and Arnold’s framework (1996), using integrated top-down and bottom-up perspectives. The model is presented in Fig. 4 (adapted). Using a sample of 111 action plans collected from six German manufacturing plants, the authors concluded that instead of competing with each other, top-down and bottom-up perspectives were complementary. Top-down action reflected the CPs, objectives and action plans, whilst bottom-up perspective emerged from operational uses and processes.

Fig. 4. Process formation for OS (adapted from [19]).

Using a sample of 1438 manufacturing plants, Singh, Wiengarten, Nand and Betts [47] studied which models could show how organizations use their operations capabilities (e.g. cost, quality, delivery). Two models were used through time to explain these capabilities use: the trade-off and the cumulative capabilities models. Still, the authors found other explanative models. These included the threshold model, in which OS achieved excellence in a core capability and threshold levels for others; the average model, reflecting that OS should achieve reasonable levels in all capabilities; the non-competitive model, aiming at OS achieving below reasonable levels in all capabilities; and the multiple model, in which the OS did not contemplate a capability pattern. The findings of this work showed that the trade-off model was not used in the real manufacturing environment.

Sustainable competitive advantage can be developed by intersecting OM and the resource-based view, as in [48]. The authors used 18 high-technology Finnish manufacturing industries for the study and analysis of models for determining competitive performance. The resource-based view was able to support operations and also the need to revise and adjust the alignment between the manufacturing strategy and the resource allocation to maintain competitive advantage.

In a study about the apparel manufacturing industry in Sri Lanka, Jagoda and Kiridena [49] used a sample of 109 firms to study the factors influencing the existence of a given OS in a firm and the different outlines of OS and its relationship with internal and external environments and performance. It was settled that alternative configurations for OS existed and all could have good performance in distinct levels of competition. Also, it was found that OS did not always follow an official protocol; rather there were forced and evolutionary modes of OS, depending on external factors and strategic capabilities.

To evaluate the incorporation of environmental and social sustainability in OS, Longoni and Cagliano [37], assessed the fitness of these CPs with BS and their effectiveness in the assembly industry. It was proposed that integrating these priorities was not creating new OS, but complementing existing ones. Further the authors claimed that these CPs complemented more the OS that were market-oriented and capability-oriented and not so much the price-oriented. The performance of firms integrating environmental and social priorities in their strategy was better than for those that did not.

IV. Operations Strategy in Services

The perspective of OS differs for manufacturing and services. It is complex to provide services in distinct cultural markets [50]. Different cultural markets have diverse expectations for services. Some companies move from one market to another with minimal changes in how they provide services, while others create an intimate relationship with their customers and assume different strategies for different markets. The paper stated that each cultural segment will be preferably attracted to service product attributes that are more related to their cultural environment. Nonetheless, when customers use a service with determined expectations (as getting foreign food), they expect nothing linked to their culture. Customization can be hard in multicultural markets and standardization can be a wise option. Organizations should be sensitive regarding this; as the metrics used in measuring service performance are intangible. Branding can be very important in services.

In [51], Kim, Kim and Kim explored the design of an OS framework for implementation in a Korean telecommunications organization. The decision making was made by using a Multi-Attribute Decision-Making analysis. The proposed framework was claimed to be a useful guideline to develop OS and to build a network management centre.

A framework for service strategy and an adaptation of manufacturing flexibility for application to services operations context were introduced by Aranda [52], and tested for Spanish consulting firms. The flexibility dimension in services addresses the need for the market introduction of new adjusted designs and services rapidly. The authors stressed the customer interaction and customization importance as demanding more flexibility from services. The direct effects of OS in financial performance were higher than the indirect effects of flexibility. Also, the direct effects of OS in non-financial performance were lower than the indirect effects through flexibility.

An alternative for service companies is to provide services through the web, as explored in [53]. The e-service is flexible and the contact between the service provider and the customer is performed through the ICT. The e-service can be restrictive concerning the viewing and hearing areas, however the customers are not constrained by distance and opening hours. There were three groups of bases in e-service operations: services marketing, service design and service delivery. The first dealt with matching the market needs with the resources owned by the organization; the second included all assets related to facilities, servers and equipment; and the third related to the delivery of products to customers.

In [54], Kim et al. developed a framework for service quality analysis and improvement, and performed a case study in a telecommunications company in Asia. The authors used the quality function deployment for collection, organization and analysis of qualitative information; and structural equation modelling (SEM) to build and analyse quantitative models for strategy upgrading. The framework had four phases. First, the construction of the house of quality (HQ); followed the analysis of the data in the HQ. Then the strategy development for improvement of customer value added. Finally the SEM analysis for improvement of customer value added.

The study in [34], focused on 190 Australian service firms. It tracked a relationship between the CPs and the areas of operational activities. The authors proposed two research questions. The first aimed at finding if there was difference in the relationship between OS and operations activities in firms performing well and in those not performing well. The second research question was a consequence of the first: in case there were differences between low and high performing firms, which were those differences and what was their pattern. From this study, the authors found that there was different alignment between strategic priorities and operations activities when comparing firms with high and low performances. For companies competing in low cost, the technology activities were more important; meanwhile, for firms competing on delivery, the most important was the relationship between delivery and logistics and scheduling activities.

To develop an OS for IT sector in developing countries, Ibrahim [32] conducted a study in a telecommunications company in Egypt. The main goal was the identification of the differentiating CPs and the market segments. Quality was the most important operational strategy and customer focus and service provision were the most important variables in sales. For projects prioritizing cost, success was not notable. Still, it was suggested that the strategy formulation could be performed after-market testing, to allow a company to adjust its CPs to market segments. The theoretical framework included CPs directly affecting the successful sales and also the market-segmentation, which indirectly influenced successful sales.

An university was used for a case study in [55], for strategy formulation in organizations. First the competitive factors were identified. Considering the organization capabilities, the areas where it was strong to compete were identified, and those competing areas where it should not compete. The SWOT analysis was used to formulate strategy. The final strategy formation used fuzzy screening technique.

In [56], were used two models of complexity theory in service innovation (Kauffman's NK model and organizational ambidexterity). The author proposed an evolutionary process for service innovation. There was a positive link amid service innovation success and the view the service provider had about service innovation as an evolutionary process. Another proposition was linked to the success of service innovation being related to small variations targeted for improving existing services. It was proposed that success in service innovation would be positively linked to major variation in finding new services. There was focus on the relevance of joint effort between service provider and customer. The success of service innovation would be attained to taking advantage of this interaction.

The service sector has more difficulty in reaching a good fit between competitive and operations strategies [21]. Lillis and Sweeney [21] studied the relationships between the view taken by the company (resource-based or market-based) for competitive strategy formulation and the strategic role adopted for operations. Furthermore, the authors used the information to understand how these relationships could improve the internal strategic fit. In the sample of firms that were used, it was found that most companies adopted a market-based view, being the organizations internally supportive of this view.

Silvestro [57] proposed the performance topology mapping to have better insight on performance drivers for developing OS and correctly manage operations in services. The author claimed that this new approach is more robust for building strategy maps, than existent methods in literature. There was a defence that the OS basis should be "empirically demonstrable performance", rather than managerial conventions. The map in the performance topology had links among performance variables to build a network of performance relationships.

V. Operations Strategy in Product-Service Systems

Nowadays manufacturing companies have shifted their orientation from only selling manufacturing-based products becoming more product-service oriented systems. Industries are keen to add services not only as “add-on” of their products but more as a bundle of total offering. This approach is called Product-Service System (PSS) where companies are offering an integrated products and services which emphasizes on value in use rather than ownership

Mathieu [58] proposed a typology for manufacturing companies wanting to integrate services in their offering. The typology included service specificity and organizational intensity. The first related to customer service, product service and service as a product; the second could be tactical, strategic or cultural. The author referred the variety of services that could be offered by manufacturing companies, depending if those companies were targeting a consumer market or a business-to-business (B2B) market. For the consumer market, the offering usually fell on distribution and repair; whereas, in B2B market, it was about the suppliers providing financing, after-sales and/or training services. Several benefits could arise from using a service strategy: financial, strategic, marketing, competitiveness, high value to customers and innovation.

In [59], Oliva and Kallenberg focused on the transition of manufacturing companies creating service organizations. The transitional process was linked to building capabilities and to finding a balanced relationship among the product end-users and the service offer. The authors focused on manufacturing firms transitioning from product providers to almost merely service providers, with the product raising minority concerns. In this transitional phase the concerns were related to changing goals, incentives, management, and others. Most organizations in the referred transition would, at very early stage, make a separation among the manufacturing and service operations.

Some products that can be found in the market have associated services. Following this, Kumar and Kumar [60], published about a conceptual framework to develop services in industrial systems and products. The authors referred the importance of service and product support in increasing customer satisfaction, loyalty, to create advertisement through customers spreading the good words about the firm and as a shield against low-cost competitors. The framework included aspects as product design features, customer's organizational culture and location. These aspects were considered the most relevant in service delivery strategy. The framework paid attention to customer requests in strategy building, which allowed organizations to shrink the gap between customer service delivery expectations and perceived service delivery.

Gebauer [61] studied the different service strategies to be included in manufacturing companies. There were four strategies in the study. These were related to after-sales service, concentrating in cost leadership and insuring proper functioning of the equipment; customer support, that invested in product and service differentiation; outsourcing partners, using cost leadership and service and product differentiation; and the development partners, that were related to research and development of services in order to make customers benefit from the developed competencies. The framework developed used a combined research on external environment and strategies. The metrics related to the external environment were competitive intensity in product and services, market growth, price and customer's choices. The strategies related to cost leadership, differentiation in products and services, the service offering and the marketing differentiation of services.

In 2009, Aurich, Wolf, Siener and Schweitzer [62] referred the crescent need customers had in having services associated to high-quality products. Hence, the authors proposed a framework with all the activities that were relevant for the configuration of PSS, using a case study to exemplify the activities presented in the framework. The proposed framework was divided in three element groups. The first was related to the basics: physical structure of the product, product life cycle and the structure of the services. The second analysed the influence of the product life cycle, as well as the impact of the service, using the data gathered from the first element group. The third represented the configuration of the PSS. The configuration regarded technical and service aspects. In the framework was established a continuous improvement of products, services, procedures and regulations.

Baines, Lightfoot, Peppard, Johnson, Tiwari and Shehab [63] presented a framework that could be used by manufacturing firms as a tool to product-services association. The fact that operations around products were connected to the materials transformation into goods was debated; services operations were about providing experiences to customers. Therefore, for product-centric servitisation, there should be a blending of extremes. The typical assembly of products and the test and repair near the customers, exist. Focus should be given to the response time and to reliability in the supply chain, because products should be readily available, and with an offering of very similar products, but with distinct supporting services. The employees should have knowledge on the product characteristics and being able to establish a reliable relationship with the customers.

Several challenges are experienced by manufacturing companies undergoing a servitisation process. This was highlighted in [64], where a single-case study was used to study the challenges faced by UK manufacturing firms that aimed at becoming product-service providers. The authors identified five categories of challenges faced by these firms: embedding product-service culture, providing an integrated offering, acquisition of capabilities to compete in services, strategic alignment, and development of supplier relationships, this is, good cooperation with the supporting network.

Another framework based on a literature review, for OS in PSS was proposed by Datta and Roy [65]. The aim of the work was to provide an aiding tool in the development of the product/service offering. The framework included four key dimensions. The first was the contract definition and included aspects as price, payment plan, technical and functional issues. The second dimension was the service provider OS, including the organisational readiness. The service delivery was related to ensuring that the service provision had a performance as specified by customers. Finally, there was the customer OS.

Olhager and Johansson [66] referred that products and services were likely to have distinct CPs. Hence, the authors provided a framework integrating manufacturing and services operations. It was considered important a joint analysis on both. The lead and chase strategies for manufacturing and services paid more attention to capacity availability and flexibility; the lag and level strategies focused on capacity use and cost efficiency. It was also a possibility that low cost operations would be desirable in manufacturing and the service demand would require excess capacity to have flexibility.

Santamaría, Nieto and Miles [67] studied the introduction of new improved services by manufacturing organizations. When manufacturing companies under servitisation process invested in human resources, they were investing in one of the critical roles in developing new skills for service innovation. Training activities were more relevant for service innovation and not so much for process innovation. Customer interaction was crucial in servitisation. R&D was a factor with more impact in service innovation than in manufacturing.

To provide a guideline for managers interested in evolving from product to services industries, Gebauer, Ren, Valtakoski and Reynoso [68], made a review on services strategic assets in manufacturing and also discussed the impact of services in industry. The authors proposed a framework with focus on the value chain expansion. The firms direct operations towards provision of new services to correspond to market demand and to maintain a competitive edge and to grow financially.

There is a common interest in understanding the practices and technologies used in successful servitization. Baines and Lightfoot [69] developed a case study in manufacturing firms that gone over a successful servitisation to reveal the practices and technologies used. The authors found six technologies and practices to deliver advanced services: facilities and location, micro-vertical integration and relations with suppliers, information and communication technologies, human resources and their skills, performance measurement and value demonstration, and business practices and customer relations.

VI. Discussion and Conclusions

This paper contributes to the existing OM literature exploring two main questions that have been missing in prior research studies. Drawing on literature addressing operations strategy, firstly we explore if there are any difference in OS in manufacturing and services organizations and what distinguishes them. Second, we explore where does the PSS in OS fall, namely does it approach more to the OS in manufacturing, in services, or a combination of both.

From the manufacturing perspective in OS, it was a common understanding that investments in technology, equipment, plant, process environment were very important decisions for OS [33, 41, 42]. The choice of the manufacturing technology was considered a very important strategic decision, from which business performance was dependable [33]. The existence of different ‘technologies’ was considered in literature [43]. These technologies were combined to attain unique product offer, creating customer value. Such studies relying on the manufacturing technology show that effective technological choices are important in OS in manufacturing. A correct investment in technology is a competitive tool.

The CPs were used to represent OS. Some authors proposed an analysis on the CPs as a combination, to better define strategy and operations, with a trade-off approach in the CPs [44]. Nonetheless, others identified the trade-off model concept as not being used by manufacturing companies in practice [47]. Other approach used the CPs as building blocks for developing a tool to aid managers in decision making and monitoring the evolution of the strategic decisions [45]. This indicates that CPs could effectively be used to represent OS.

A link among studies in manufacturing organizations was the prominent need to correctly connect the OS formulation with the CPs and BS, to provide competitive advantage and increased market share for firms. In [22, 30], was stressed the need to align OS and BS. Customer demand was found very important for competitive and manufacturing strategies [46].

There was no agreement on the best perspective for OS. In [22] were adopted top-down and resource-based perspectives; and in [48], a purified resource-based view. In [19], a complementarity of top-down and bottom-up perspectives was found beneficial. Building on literature, we believe the development context of OS dictates the best approach.

OS does not always follow strict official protocols. It is rather more adaptive, depending on external factors and on strategic capabilities [49]. For example, more recently, social and environmental concerns were found to be very important for manufacturing organizations pursuing competitive edge, by complementing existent OS, rather than creating new OS [37].

Considering the above paragraphs, there seems to be a time evolution on the important assets in OS. First, technology appeared to be the focus of research. Followed the highlight on the CPs to better describe and translate OS. Then, the focus was on the alignment of CPs, OS and BS. The perspective on OS goes from a top-down approach to a blending of top-down and bottom-up perspectives. Finally appeared new CPs concerned with the environment and society to redefine current OS and the notion that the OS plan is not a static, but an ever-changing reality. Even though this outline appears strong, we acknowledge that this evolutionary conclusion might not be completely accurate due to the reduced number of papers reviewed and their limited time frame.

Regarding OS in services, three of the analysed papers included the operations perspective in telecommunications firms [32, 51, 54]. In [51] was introduced a framework for development of OS, which indicates that in services, there is also the need to have good planning of the operations actions. Furthermore, improvement in telecommunications services was a focus; it meant to increase the customer value added [54]. A great focus on the service quality was given in [32, 54]. In [54] was given a tool for service quality analysis and improvement, whilst in [32], quality was found to be the most important CP.

In fact, the strategy formulation in service was pointed as decisions to be tailored after a market assessment [32]. This leads to a finding in another of the analysed paper, [55], that points to the importance of organizations to clearly define their strengths and weaknesses to identify the areas where they should be competing or not. Moreover, manufacturing concepts as flexibility were adapted to fit the services context [52]. Another issue referred in the services literature was the difficulty in adapting a service to distinct cultural markets [50].

The service sector finds more difficulties in reaching a good fit between competitive and operations strategies [21] and service providers tend to focus more on a market-based view. The alignment between strategic and operations priorities is highlighted [34] There is also the need to provide innovative services to the markets, perhaps even through the web [53].

Comparing OS in manufacturing and in services, some commonalties can be found. For both, it is important to find an alignment between the strategic activities and the target market. Services and manufacturing organizations should clearly define in which priorities the organization aims at competing. Also, the OS was pointed not to be adaptive to external factors.

Several differences can be observed. In services, a great focus is given to quality; meanwhile, for manufacturing, the focus does not fall into a single CP, but rather a set of CPs. The difficulty in adapting a service to distinct market segments is common; also, assessing a service performance is harder than measuring the performance in manufacturing environment. In services, companies tend to focus more on the market view, which is not the same as in manufacturing, where there is an understanding that different views can be successful, depending on the business context. Even though technology was also referred in the services literature, a much higher importance was given to technology in the manufacturing literature. The environmental and social matters were given more importance in the manufacturing literature.

The above two paragraphs answer to our first research question. There are several differences among the implementation of OS in manufacturing and services that indicate the higher difficulty in evaluating services. Some commonalties were also found. This leads us to the conclusion that it is difficult to clearly distinguish all the characteristics differentiating strategic practices for manufacturing and services organizations. The best practices always depend on the competitive context and, at times, what is applied to manufacturing can be applied to services and vice-versa.

In PSS, the association of services to products has been pointed to increase customer satisfaction and loyalty [60], innovativeness and competitiveness [58]. Some challenges were identified for firms switching from product providers to providers of coupled product-service. The integration of a services culture in manufacturing environment is not straightforward [64], and often, companies early separate between manufacturing and services operations [59].

Several frameworks in PSS were identified [60, 62, 63, 65]. Albeit conceptually different, all combined product and services features and customer relationships. Therefore, the blending of product and service, and their orientation towards customers is what characterizes PSS frameworks.

Product-service providers can compete in dimensions, as cost, product or service differentiation [61]. Indeed, products and services were pointed to have distinct CPs [66]. Hence, there should be a joint analysis on products and services, since a blending of operations characteristics of both needs to be considered to undergo successful servitisation process.

Human resources and R&D funds were considered critical in a correct product-service provision. R&D was more critical for services innovation than for product innovation [67].

Considering the above, we now face research question number two. Following the line of thought in the paper [63], we believe that OS in PSS results from a blending of strategies adopted for manufacturing and for services. A high focus in customer and in human resources is crucial for PSS, which is similar to what happens in service provision. Also a good alignment with suppliers and the cost efficiency advantage acquired for the correct processing choice in manufacturing organizations, appear as critical assets in PSS. A summary of the main findings of this paper and the challenges of the area can be found in Table II.

Table II. Summary of findings and the challenges of the area

Manufacturing	**Services**	**PSS**
-Alignment of strategy and target market; -Clear definition of CPs; -Focus on sets of CPs; -Technology; -Environmental and social matters.	-Alignment of strategy and target market; -Clear definition of CPs; -Focus on quality; -Service adaptation to market segments; -Hard to measure performance.	-Blending of OS in manufacturing and services; -High focus on customer and human resources; -Good alignment with suppliers; -Cost efficiency.
Challenges		
-Appropriate technological choices; -Good alignment of CPs, BS, and OS; -Strategic alignment with the target market; -Good alignment with suppliers -Balancing the roles of manufacturing and services.		

This study contributes to both the OM and strategy literature streams. We provide two major contributions to the existent literature. First, we analysed the differences in OS in manufacturing and services organizations. This led us to concluding that the diving line between manufacturing and services can be blurred, even though several differences were found. Concerning to the PSS, in the line of previous publications, we believe that OS frameworks follow a blending of the strategy adopted in manufacturing and in services.

Acknowledgement

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Paper A2

Towards a System Dynamics approach for performance evaluation of assembly production areas

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Paper presented at the 2016 EurOMA conference, Trondheim, Norway

Abstract - Constantly changing markets and customers' demand for customized products are critical for assembly systems that have to be flexible and adaptable. Challenges arise when deciding how to organize and configure resources and processes. Therefore it is the purpose of this work to study the performance of different assembly systems' configurations - line, hybrid and parallel -, using a System Dynamics simulation model in an illustrative case study. The model considers a Kanban production system and no material constraints. Each of the configurations was assessed considering quality problems, different workers' performance and workstation stoppage by random failures and preventive maintenance.

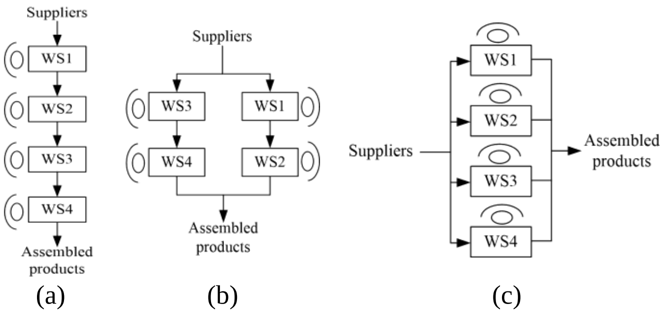
Keywords - Simulation, System Dynamics, Performance

Introduction

Constant market's change in demand and customer expectations shorten products' life-cycles (Matt, 2013), making flexibility and adaptability critical for manufacturing systems (Kuzgunkaya and ElMaraghy, 2006). With increased attention given to customization (Efthymiou et al., 2014), companies are pushed to assemble more products (Wang and Hu, 2010). From the operations perspective, many companies are exploring "assembly-to-order" strategies to reduce lead times and the response time to their customers (Elhafsi and Hamouda, 2015). Nonetheless, adjusting operations from a high-volume, low product variety perspective to a low-volume, high mix perspective is challenging when deciding how to properly organize resources and processes (Heilala and Voho, 2001). The configuration of the systems has high impact in performance (Wang and Hu, 2010); hence, to be able to assembly efficiently a high variety of products in small quantities, operations managers face uncertainty in predicting the impact of the configuration of assembly areas and improvement decisions in the future production system's productivity. The following research question arises:

RQ: How to organize and configure manufacturing resources to maximize overall production productivity?

Our study aims to explore the above research question by assessing the performance of different assembly systems' configurations: line, hybrid and parallel, as depicted in Figure 1, by using a System Dynamics (SD) model. SD helps understanding systems better (Sterman, 2000); and is simple and flexible for modelling of industrial management problems (Georgiadis and Michaloudis, 2012).



(a) (b) (c)

Figure 1 – Assembly systems configurations which were modelled and simulated using SD. (a) Line; (b) Hybrid; (c) Parallel.

Our foremost contribution relies in contributing to the SD literature, with a model that evaluates different assembly systems configurations.

The remaining of the paper is organized as follows. First, the research hypotheses are presented; follow some applications of SD to manufacturing in literature. The SD model is described and the assumptions used to build the model are presented. Then different case scenarios are analysed and the results are presented and discussed. The paper ends with the most important conclusions and future research directions.

Research Hypotheses

Assembly systems are used to assemble parts of a final product. Most assembly systems had a line configuration; however, with technological improvements new alternatives emerged (Udomkesmalee and Daganzo, 1989). Other systems have machines (or workstations) in parallel to obtain higher production or reliability (Dallery and Gershwin, 1992). According to Dallery and Stecke (1990) and Magazine and Stecke (1996), the most desirable configuration for workstations in an assembly system is purely parallel, so these can operate independently from each other. If it is not possible to implement a pure parallel system, most workstations should be in parallel in the centre of the line, in a hybrid configuration. As stated by Udomkesmalee and Daganzo (1989), in a serial line configuration workstations might not work at an optimal rate, and quality can be affected as there might not be sufficient time to finish operations, affecting performance. Considering this we propose the following hypothesis:

H1: Configuration of assembly production areas with high number of assembly operations positively influences performance of assembly systems.

The performance of the assembly systems will be evaluated for the total number of products which were assembled, the throughput as the average number of parts produced per hour, and the order lead time (OLT) – average, standard deviation (Std.) and coefficient of variation (CV).

Particularly relevant for overall productivity, is the fact that manual work assembly lines benefit from workers' capabilities (Folgado et al., 2015). Task repetition leads to variable task completion time. Learning results from task repetition, depending on the learning rate (Otto and Otto, 2014). The workforce skills impact performance at the plant level (Stratman et al., 2004). Hence, we propose:

H2: Stronger worker skills and experience (initial task completion time and learning rate) positively influence performance of assembly systems.

Disturbances and unplanned events over the plan execution are issues of great relevance for production productivity. Commonly, machines and tools are involved in assembly systems. If failure occurs, the assembly resource won't process materials, and will not supply the assembly system downstream nor remove material from the system upstream of its position. Machine downtime affects the system, by starving it downstream and blocking it upstream. Buffers decouple the machines, reducing the effects of blockage and starvation (Dallery and Gershwin, 1992). Thus we propose:

H3: The existence of buffers between assembly resources (e.g. machines) will positively influence assembly systems' performance.

System Dynamics in manufacturing systems

As referred by Sterman (2000), SD is a group of tools which allow understanding both structure and dynamics of complex systems. It is a rigorous modelling tool that helps exploring and evaluating different systems' configurations. SD, together with systems thinking, provides understanding of the relationship among the performance of an organization and its internal structure and operating policies.

SD has four basic components: the system, the feedback loops, levels and rates (Yim et al., 2004). The system must have a defined boundary to be analysed, and the elements which interact inside the system boundary define the system. The feedback loops (reinforcing or balancing) establish how elements affect each other. These are expressed by causal-loop diagrams. Levels, represented by stock levels, refer to elements for a given time interval and rates reflect how the system behaves, e.g., hourly production.

Nowadays, the industrial applications of SD range from business, to manufacturing, services, and operations. SD modelling is extremely versatile, which explains its broad range of applications (Jahangirian et al., 2010).

Following are some examples of the application of SD to manufacturing modelling and performance evaluation. Georgiadis and Michaloudis (2012) built a model to improve performance by measuring the work in progress (WIP), the average number of products in process in the workstations, the average backlog customer orders, and the average number of tardy jobs. Khataie and Bulgak (2013) used SD to create a decision support model which helped identifying value added from non-value added activities, hence controlling the cost of quality. The model intended to track real time alterations to changes in the cost of quality related to manufacturing activities. In Mendoza et al. (2014), the authors explored different aggregate production planning policies in a manpower intensive supply chain, by using SD modelling; and assessed the impact that the variability associated to some model elements had in the system performance. Considering a serial make-to-stock manufacturing system, Jaipuria and Mahapatra (2015) built a SD model to analyse response and performance under different types of uncertainty, as machine failure, supplier uncertainty, demand uncertainty, among others.

System Dynamics model description

In this paper SD is used as the modelling methodology. To build the models for each of the assembly configurations (as in Figure 1), operating under different assumptions, and conduct the simulations, we used the simulation software Vensim DSS.

Model assumptions

To build the model we made some assumptions. First, we considered that the factory works 8 hours a day, for 22 days in a month, yielding a total simulation time of 880 hours. The TIME STEP was set to 0.125 hours as it should be smaller than the shortest period of time that can significantly change the model behaviour. The integration type was Euler. There are four workstations and the number of products being produced can be set as desired. Each workstation can process one type of product at a time. There are no supplier constraints or material shortage.

Mathematical modelling and diagrams

In the model, the production considers that each workstation can only be processing one type of product at a time. In order to ensure this constraint, we defined a production decision based on the Kanban system, with colour cards representing product levels.

The model view in which is decided which product will be produced at each time step of the simulation, as in Figure 2, considers a supermarket (*SPM*) where finished products are stored. Simulations start considering the *SPM* is at full capacity, given by the *desired maximum supermarket capacity*. The model considers that when an order arrives which requires more supermarket space than the *desired maximum supermarket capacity*, there is a temporary increase in capacity. The total number of products in the *SPM* depletes with the deliveries of products (*Deliveries* = *Deliveries to customers*) and increases with *Production*. The *orders* arriving at the production plant are given by a random normal distribution, whose parameters vary with the product type. In case the products are available in the *SPM*, these will be automatically delivered; otherwise, there is the need to produce new products and deliveries must wait. To ensure that *SPM* levels will never be negative, deliveries will occur in case the *SPM* levels are higher than the *ORDER BOOK* levels for all products. Orders are always delivered complete.

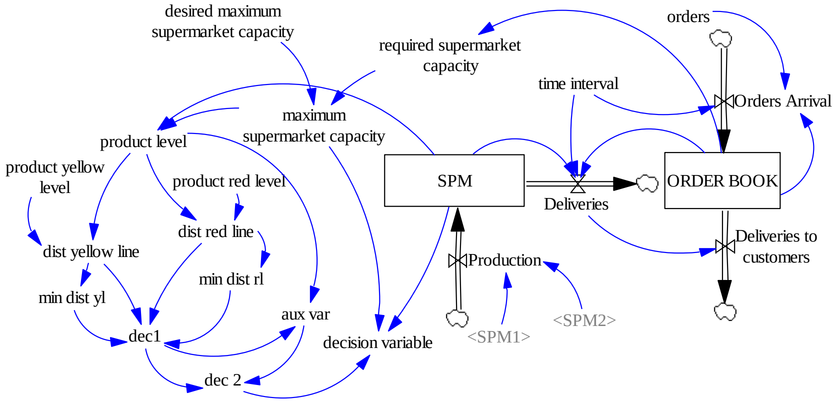


Figure 2 – Decision of which product to be produced at each time, based on a Kanban system.

For the Kanban system we considered two product levels: the *product yellow level* and the *product red level*, which represent the product levels which should not be exceeded to ensure that production runs smoothly. *Production* can only occur in case the number of products in the *SPM* is below the *maximum supermarket capacity*. The *Production* value is given by the production rate from each of the three different layouts considered. Meanwhile, the *product level*, which is the difference between the *maximum supermarket capacity* and the products that in fact exist in the *SPM*, will increase. Therefore, the difference between the *product level* and the *product yellow level* (*dist yellow line*) and the difference between the *product level* and the *product red level* (*dist red line*), will decrease. The minimum distance to each line is calculated and the product to be produced will be the one which has the smaller distance to the yellow line. In case the product level is higher than the product yellow line, the product which has the smaller distance to the red line will be produced, as the *dec1* equation (1) shows:

dec 1= IF THEN ELSE(min dist yl$\geq$0, IF THEN ELSE(dist yellow line[products]= min dist yl, 1 , 0) , IF THEN ELSE(dist red line[products]=min dist rl, 1 , 0)). (1)

The only exception exists when the *SPM* is at its full capacity for a given product. Herein, the product is not considered for deciding which product should be produced. In case there are two or more products which have the same distance to the yellow or the red lines, there is an auxiliary variable (*aux var*) which retrieves the product levels for those products and another preliminary decision variable, *dec2* which, among those products, selects the one which has the maximum *product level*, and the product that will be produced will be that one, as in equation (2).

dec 2=IF THEN ELSE(SUM(dec1[products!])=1 , dec1[products] , IF THEN ELSE(aux var[products]=VMAX(aux var[products!]), 1 , 0)). (2)

In case there is still more than one product selected, no production will occur so that in the next iteration of the simulation some differences are generated and only one product is selected, as the final *decision variable*, in equation (3) decides:

decision variable=IF THEN ELSE(SUM(dec 2[products!]) = 1: AND: SPM [products] < maximum supermarket capacity[products], dec 2[products] , 0). (3)

We considered that workstations may stop, as in Figure 3(a). Two possible reasons lead to workstation stoppage: (i) The workstation randomly fails due to unpredictable problems; (ii) The workstation stops for preventive maintenance. The random workstation stoppage occurs under a normal distribution, $N(0,0.01)$. The stoppage depends on the *sigma level* that governs the production process; this is, the workstation stops in case the random number generated by the normal distribution falls outside the boundary given by the interval [-σ**sigma level*; σ**sigma level*]. The higher the *sigma level*, the higher the machine reliability and less probability exists of *random failure*. As for the stoppage due to *preventive maintenance*, it is assumed that machines stop for one hour, *inspection time*, every twenty four hours working, *time between inspection*.

Some disturbances to production can occur by the action of the workers, as in Figure 3(b). There is one worker assigned to each workstation. When the workers perform a task for the first time, they will require a certain amount of labour hours to complete that task, given by the *initial production times*. Afterwards, by repeating the tasks, workers will learn and decrease the time spent in production, until reaching an *ideal production rate*. Time will decrease at a uniform rate, given by the *learning percentage*. The direct labour hours that a worker spends performing a task are given by a learning curve, which follows equation (4):

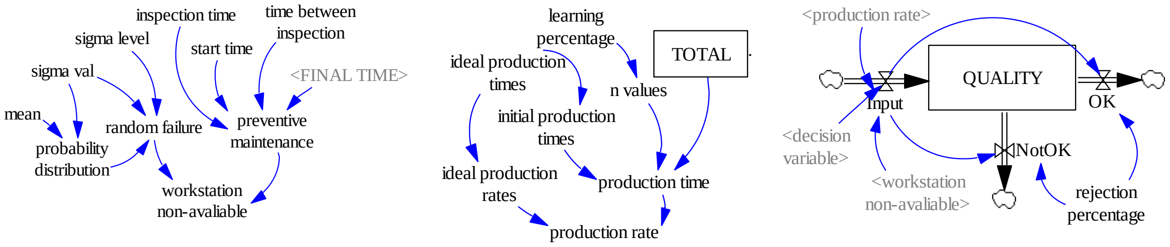
$$Y=Kx^n, \qquad (4)$$

where Y corresponds to the direct labour hours required to produce the xth unit, K is the direct labour hours required to produce the first unit, x is the cumulative unit number, and n is the learning index, given by equation (5):

$$n=\log\phi/\log 2, \qquad (5)$$

where ϕ is the learning percentage (Yelle, 1979). Learning will occur when one unit which complies with the quality standards is produced in each workstation.

Quality problems can occur during production, and not all parts fabricated will be exempt from defects. We assumed that each product and workstation will have an associated *rejection percentage*, as Figure 3(c) shows. The *OK* flow accounts for the production which is according to quality standards and the *NotOK* flow corresponds to parts which did not meet the quality standards and were rejected. Rejected parts are not re-introduced in the system hence no rework flows exist in the model.



(a) (b) (c)

Figure 3 – Disturbances that can occur during production. (a) Workstation failure; (b) Non-ideal production rates depending on learning capabilities from workers; (c) Quality problems.

To study the impact of buffers in the performance of assembly systems, we placed buffers between WS1 and WS2, WS2 and WS3, and WS3 and WS4 in the line configuration (Figure 1); in the hybrid configuration we used one buffer between WS1 and WS2 and another between WS3 and WS4. In the parallel configuration, no buffers were used because workstations are independent and there are no supplier constraints.

Numerical example – case scenarios results and discussion

The SD model was validated considering some tests suggested in the SD literature (Sterman, 2000). The model dimensional consistency was evaluated and extreme conditions testing were conducted. The model was tested for zero orders arriving and we checked that neither *Production* nor *Deliveries* occur.

In all the simulations we considered a total of four products which can be produced (P1, P2, P3, P4). The constants used in model are given in Table 1. The random normal probability distribution in Table 1 accounts for the following parameters: RANDOM NORMAL (minimum, maximum, demand mean, demand standard deviation, seed).

Table 1 – Values of the constants used in the model and respective units

Constant name	**Value**	**Units**
Ideal production time P1	2	Hours/Unit
Ideal production time P2	4	Hours/Unit
Ideal production time P3	8	Hours/Unit
Ideal production time P4	12	Hours/Unit
orders P1	INTEGER(RANDOM NORMAL(0, 100 , 8 , 3 , 0))	Units
orders P2	INTEGER(RANDOM NORMAL(0, 100 , 6 , 2 , 0))	Units
orders P3	INTEGER(RANDOM NORMAL(0, 100 , 4 , 1 , 0))	Units
orders P4	INTEGER(RANDOM NORMAL(0, 100 , 2 , 1 , 0))	Units
desired maximum supermarket capacity	45,28,18,10; (P1,P2,P3,P4)	Units
Product yellow level	28,15,8,4; (P1,P2,P3,P4)	Units
Product red level	36,20,12,5; (P1,P2,P3,P4)	Units

Base Case

In the base case, we considered that there was no workstation stoppage, no differences among workers' skills and that all workers were performing their tasks in the ideal time in all workstations, and that all final products met the quality standards. The results for each layout configuration were obtained for the total number of products which were assembled, the throughput, and the OLT – average, Std., and CV, as in Table 2.

Table 2 – Total number of final products achieved with each layout configuration, the throughput, and the average OLT, OLT standard deviation, and OLT CV

	Final Products (Units)				Throughput (units/hour)				OLT (Hours)		
	P1	P2	P3	P4	P1	P2	P3	P4	Average	Std.	CV
Line	323	203	134	82	0,367	0,231	0,152	0,093	21,86	14,58	0,67
Hybrid	298	218	142	76	0,339	0,248	0,161	0,086	23,14	14,37	0,62
Parallel	252	232	140	80	0,286	0,264	0,159	0,091	22,92	14,43	0,63

As the results in Table 2 show, there are no significate differences among the results of the three configurations. Even though the number of final products achieved for P1 is higher for the line configuration, the parallel configuration achieves more production of P2. This is a consequence of the fact that the orders are given by a random distribution, hence the production requirements will vary. As for the OLT, it is very similar for the three configurations, which is explained for the fact that the three configurations are working with the same cycle time. The standard deviation is approximately 14.5 hours for the three situations, which is high when compared to the average. To assess the causes, we doubled the *desired maximum supermarket capacity* value, and later reduced its value to half to understand its impact in the OLT average and Std.. Decreasing the *desired maximum supermarket capacity* had no impact in the OLT average value, but decreased the OLT standard deviation 1,3 times. Reduction of the OLT average by 1,4 times and increase of the OLT standard deviation 1,5 times were verified when doubling the *desired maximum supermarket capacity*.

The CV value is slightly higher for the line configuration, which indicates higher variability in the OLT for this configuration than for the hybrid and parallel configurations.

Assessing the impact of workstation failure and quality problems

To compare the performance of the different systems' configurations, we considered the workstation failure and quality problems. Each configuration was tested for a *sigma level* of 3 in all workstations and *rejection percentage* given by a random normal distribution *N(0.1,0.01)*. The results of the simulations are presented in Table 3, for the total number of products achieved for each product type, the throughput, and the OLT (average, Std. and CV).

Table 3 – Results obtained for each layout configuration, under disturbances related to workstation failure and quality problems

	Final Products (Units)				Throughput (units/hour)				OLT (Hours)		
	P1	P2	P3	P4	P1	P2	P3	P4	Average	Std.	CV
Line	132	93	63	30	0,150	0,106	0,072	0,034	50,30	25,22	0,50
Hybrid	120	97	62	31	0,136	0,110	0,070	0,035	48,65	29,72	0,61
Parallel	254	192	126	59	0,289	0,218	0,143	0,067	25,15	15,67	0,62

As the results from Table 3 show, for the parallel configuration, more final products are achieved than for the hybrid and line configurations, and the throughput is also higher. In what concerns to the OLT, the average and Std. values for the OLT are smaller for the parallel configuration. This is a good indicator that the parallel configuration has a better performance for the accessed indicators than the other two configurations, even though the CV value is higher and more variability is likely. The results for all configurations, when compared to the base case scenario are worse, with decreased total number of final products achieved and increased OLT average, and Std.. When comparing results for the line and hybrid configurations, the hybrid configuration achieves better results, with lower average OLT, but with more variability, as the CV value is higher. However, it is hard to evaluate the results for the total final products achieved and the throughput, as these are similar for the two configurations.

These results are partially supportive of H1, because the parallel configuration has better performance, but the differences among the hybrid and line configurations are difficult to access. Other parameters should be evaluated. More simulations should be run with different parameters and the isolated effects of the workstation failure and quality problems should be evaluated. However, due to the reduced space, we are not presenting those results in this paper. Assessing a cost dimension would be valuable, as a trade-off analysis could be performed to understand if the better production results obtained for the parallel configuration would worth the investment costs.

Assessing the impact of differences in workers' skills

To assess the impact of different workers' skills in assembly systems, we considered that the only interference in assembly is the time variation associated to the workers completing their tasks in different times.

Three scenarios were studied: (i) All workers have the same *initial production times* and different *learning percentages*; (ii) All workers have different *initial production times* and the same *learning percentage*; (iii) All workers have different initial production times and different learning percentage, as in Table 4. The parallel configuration was simulated to obtain the results in Table 5. In this case, we are calculating the throughput for each workstation (independently from the type of product), to assess the impact of workers with different skills in different workstations.

Table 4 – Parameters values, learning percentage (LP) and MF (initial production times= MF x ideal production times), used in the simulations for each scenario

Scenario	(i)		(ii)		(iii)	
	LP (%)	MF	LP (%)	MF	LP (%)	MF
WS1	95	2.5	95	2.0	95	2.0
WS2	90	2.5	95	1.5	90	1.5
WS3	85	2.5	95	2.5	85	2.5
WS4	87	2.5	95	1.7	87	1.7

Table 5 – Total final products, throughput, and OLT for each scenario, for the parallel configuration

Scenario	Final Products (Units)				Throughput (units/hour)				OLT (Hours)		
	P1	P2	P3	P4	WS1	WS2	WS3	WS4	Average	Std.	CV
i	159	124	72	43	0,092	0,110	0,137	0,125	41,196	26,11	0,63
ii	174	147	86	47	0,120	0,164	0,095	0,144	36,804	20,88	0,57
iii	220	171	110	53	0,120	0,190	0,142	0,186	27,54	18,76	0,68

As the results in Table 5 for scenario (i) show, it is clear that a lower *learning percentage* in WS3 is helpful and higher throughput is achieved. For scenario (ii) results show that for workers with the same *learning percentage*, having a lower *initial production time* is beneficial. For the scenario (iii) better performance is obtained for WS2 and WS4. This is a consequence of the intermediate *initial production times* and *learning percentages*. Even though WS3 has higher *initial production time*, it has lower *learning percentage* and performs better than WS1, which has lower *initial production time*, and higher *learning percentage*. Hence, the *learning percentage* has higher impact in the performance of parallel assembly systems than the *initial production time*. Better performance is achieved for better worker skills, which supports H2.

Further analysis can be performed by simulating the line and hybrid configurations for the above three scenarios. Also, the level of investment need to provide the workers with the skills needed to achieve a certain performance level could be analysed.

Assessing the impact of adding buffers

Buffers decouple workstations. To assess the impact of buffers in the performance of assembly systems, we introduced buffers in the line and hybrid configurations. The buffers capacity is four units. The parameters used were the same as when assessing the impact of quality problems and workstation failures. The results are as in Table 6.

Table 6 – Total final products, throughput, and OLT, for each scenario, for the line and hybrid configurations, using buffers between workstations

	Final Products (Units)				Throughput (units/hour)				Order Lead Time (Hours)		
	P1	P2	P3	P4	P1	P2	P3	P4	Average	Std.	CV
Line	180	150	94	41	0,205	0,170	0,107	0,047	33,33	13,98	0,42
Hybrid	216	156	112	54	0,245	0,177	0,127	0,061	29,40	17,77	0,60

Comparing the results in Tables 6 and 3 becomes clear that better performance is achieved when buffers are used. By decoupling workstations, buffers reduce the dependence among workstations. The buffer sizes were not optimized. The above supports H3. The performance of the hybrid and line configurations with buffers becomes more similar to the performance of the parallel configuration (Table 3) under similar constraints. A cost analysis would improve this work.

Conclusions and future research directions

The most important contribution of this paper relies in the evaluation of different assembly configurations, which could provide important managerial implications.

We have successfully implemented a SD model to evaluate the validity of the proposed hypothesis. The most important results support the hypothesis, however, further testing and model improvement should be performed to retrieve more conclusions. One possible improvement to the model should include a cost analysis so that a trade-off evaluation could be made for more accurate judgement of the different assembly configurations.

This work shows that SD is a suitable methodology to assess the performance of systems under different configurations. However, for more detail other methodologies should be considered, as the discrete event simulation.

Some model limitations should be addressed in the future. This should include, among others, considering the influence of suppliers and material shortage, forgetting effects of tasks by the workforce, more workstations and a cost dimension to the model.

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