FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

A methodology for controlling the consequences of demand variability in the design of manufacturing systems

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Abstract

An uncertain future

Today's unprecedented product demand changes flood the global market. Staying competitive is now a matter of responding quickly and cost-effectively to variability. To address this paradigm, manufacturing flexibility is a key aspect to tackle. Studies show that integrating flexibility in design of manufacturing systems increases their performance by 25%, yet stable decision-making application procedures are still not very well established. This dissertation proposes a solution methodology for this problem.

Aiming to control the consequences of product demand variability, an integrated approach of screening and simulation modeling has been developed. Applied to a case study in the furniture manufacturing industry, the methodology highlighted numerous opportunities of improvement in the manufacturing site.

By applying a flexible design, the overall performance goals were reached and a plan of action was initiated. The results support the proposed methodology as a viable solution for the problem addressed, nevertheless future success involves more than the pure application of this procedure, as flexibility is also a way of thinking.

Resumo

Um futuro incerto

Atualmente, mudanças, sem precedentes, da procura caracterizam o mercado global. Permanecer competitivo é agora uma questão responder rapidamente e de forma económica à variabilidade. Para enfrentar este paradigma, a flexibilidade é um aspeto chave a considerar. Estudos mostram que integrar flexibilidade no design de sistemas de produção aumenta a sua performance em cerca de 25 %, no entanto os procedimentos para a sua implementação ainda não se encontram devidamente estabelecidos. Esta dissertação propõe uma metodologia para solucionar este problema.

Tendo em vista o controlo das consequências da variabilidade na procura, foi desenvolvida uma abordagem integrando simulação e screning. Aplicada a um caso de estudo da indústria de mobiliário, a metodologia destacou inúmeras oportunidades de melhoria no local.

Ao aplicar um design flexível, as metas gerais de desempenho foram alcançadas e um plano de ação foi iniciado. Os resultados suportam a metodologia proposta como uma solução viável para o problema abordado, no entanto, o seu sucesso futuro envolve mais do que a pura aplicação deste procedimento já que a flexibilidade é também uma forma de pensar.

Acknowledgments

This thesis marks the conclusion of a five years chapter of my life. Five year of incredible challenges and amazing experiences throughout. Memories and lessons learned that fill this amazing journey, from the first steps in my faculty to the last ones in my internship.

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Lastly for the ones at home, my family, that anxiously await the moment I conclude this dissertation, to have their living room back! Thank you for the patience and support.

“The only constant is change, continuing change, inevitable change”

Isaac Asimov

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Abbreviations and Symbols

FMS	Flexible Manufacturing Systems
DES	Discrete Event Simulation
MHS	Material Handling Systems
MTS	Make To Stock
BOF	Boards On Frame
PFF	Pigment Furniture Factory
BOS	Board On Style
F&W	Foil Wrapped
L&P	Print Lacquered
MTBF	Mean Time Between Failures
MTR	Mean Time Between Repair

Chapter 1

Introduction

Nowadays, the manufacturing industry is facing a turbulent and rapidly changing environment [11]. With increased customer requirements, endless changing needs, improved manufacturing methods, new technologies and government regulations [13], companies are inevitably fated to respond to shorter product life cycles, higher product variety, increasingly unpredictable demand, and shorter delivery times [11, 13–15]. Uncertainty thereby is becoming an intrinsic characteristic of the market, an inevitable consequence of the complexities generated by technological advancements [16], and it is of common agreement that will continue to grow in the twenty-first century [15, 17].

In the face of fierce competition, fluctuations in product mixes and volumes need to be easily accommodated by manufacturing systems, shifting quickly from one product line to another without major retooling, resource reconfiguration, or replacement of equipment [18]. To maintain a competitive position, manufacturing companies now require to cope quickly and efficiently with **change** [11, 15]. Achieving low cost and high quality is no longer enough to guarantee success [16, 19]. It is vital to control the consequences of demand variability.

This chapter will continue with the following structure, firstly it is presented the motivation for applying principles of flexibility in design of manufacturing systems to control the consequences of demand variability, then the motivation for this work is presented, continuing afterwards with the objectives of this dissertation and finishing with the document structure presentation.

1.1 The reason for flexibility

Vast scientific contributions in the literature of manufacturing flexibility describe and support the purpose for flexibility integration [2, 11–14, 16, 17, 19–28]. Following some of the contributions, as [11, 22], **change** is the reason for flexibility. The need to handle unexpected changes, both within the manufacturing system and outside, without penalties for the manufacturing industry, as well as, the current necessity of offering a vast variety of products drives flexibility [11, 13, 15, 22].

Considered as one of the most sought-after properties of nowadays, flexibility is a crucial requirement for organizational survival of production oriented companies [16, 29]. As flexibility improves the utilization of the resources in a system, increasing its operational performance, as well as, its ability to cope with internal and external disturbances under tight due dates targets, manufacturing responsiveness of the system significantly rises [11].

Flexible designs appear as the way control product demand variability. The capacity to absorb fluctuations in demand economically, to develop and introduce new products quicker [24], using existing facilities, are seen as the drivers for designing flexible manufacturing systems [13, 14].

Flexible designs enable cost-effectively responses to changing circumstances and permit substantial improvements in the overall average returns of a manufacturing system, that is, the expected value [25, 30].

Real word case studies also provide evidence that flexibility in design is an effective way to improve the expected performance of systems in uncertain environments, with improvements in performance by 25 percent and more [25]. In short, by identifying and exploiting opportunities for flexible alternatives, better designs that deliver best performance can be achieved [9, 25].

Neufville and Scholtes [25] underlined three kinds of advantages that can be accomplished with the right kind of flexibility in design:

1. an increase of output of the manufacturing facility;
2. an better control of the risk;
3. an reduction of initial capital expenditures, leading to smaller and inherently less expensive initial systems due to distribution of investments under the life cycle of the system.

It stays latent the importance of flexibility for industrial companies.

1.2 Motivation

Flexibility is now seen as a fundamental approach to systems design [25]. Following the relation between designs as a function of the system's objectives and the environment characteristics graphically characterized by [1] (figure 1.1) the consensus among scientific contributions is emphasized. Current approaches, such as optimized design and robust ones, do not recognize the reality of a manufacturing system [25]. Traditional practices do not meet the necessary requirements of today challenges. Assumed conditions, such as demand, are constantly changing and management reactions are active rather than passive [25]. Systems are routinely subjected to changing environments and changing objectives. The fact is that conventional layouts, such as product, process, and cellular layouts, do not meet these needs.

What is seen consecutively is that the layout performance deteriorates as product volumes, mix, or routings fluctuate [31], as a consequence of false assumptions of stable demand. [12]

Functional layouts, notoriously known by its material handling inefficiency and scheduling complexity, in turn lead to long lead times, poor resource utilizations and limited throughput rates. Changes in product mix and/or routings makes this layout vulnerable to low levels of performance, costly re-layout of the plant and an expensive redesign of the material handling system. [12, 32]

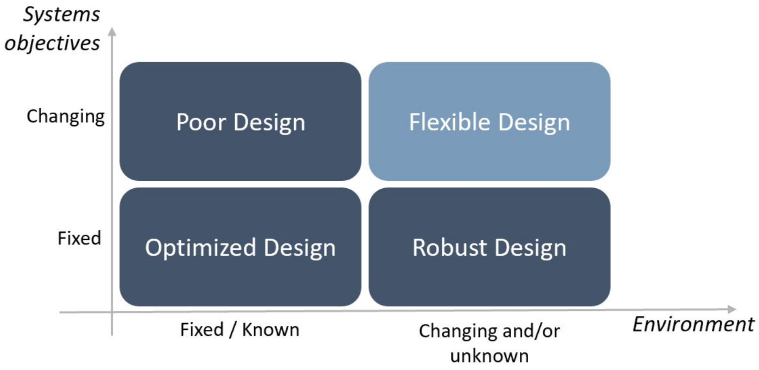


Figure 1.1: Design dimensions regarding system's objectives and environment (source: [1])

Cellular layouts, for instance simplify work flow and reduce material handling. However by considering a stable demand, long product life cycles and little allowance for inter cell flows, the layout becomes inefficient when product requirements fluctuate or new products are introduced [33, 34]. In literature some alternative cellular structures already appear in order to try to combat this characteristic such as overlapping cells [35], cells with machine sharing [33], and fractal cells [36, 37].

The fact remains that layout design methods, whether for functional or cellular layouts, have been largely based on a deterministic paradigm, assuming design parameters as product mix, product demands, and product routings to be known with certainty [38]. However, when the system is subjected to demand variability its performance is greatly affected.

In short, there is a need for layouts that are more "flexible, modular, and easy to reconfigure" [12]. The system's ability to **compensate changes** and tackle the necessary variations will define the success of the design nowadays [25]. Flexibility is a key asset to achieve such that, as advocated by [1]. Unlike all other designs, it already consider features that enable the system to respond to a range of possible circumstances, either automatically or under the direction of system managers and it is fully prepared to include modifications whenever it may be necessary [26].

The push to make factories more flexible has been spreading throughout manufacturing industries for this reasons. However, managers in several industries are finding it frustratingly difficult to apply [5, 11, 26], as "the procedures for creating effective flexibility in design are not well established" [25]. Consequently, research on the matter of flexible design is crucial to the future of manufacturing industries.

1.3 Dissertation objectives

This dissertation presents an approach to design plant layouts in stochastic environments, which aims controlling the consequences of product demand variability in manufacturing systems.

Integrated in an ongoing project between INESC TEC and IKEA Industry of Paços de Ferreira, this dissertation intents to contribute with methods for designing flexible layouts.

The project in question is focused on increasing the overall competitiveness in the long term spectrum of IKEA Industry of Paços de Ferreira. The project rollout is based in 3 major phases, intrinsically related to each other. An extensive analysis of the current state of the BOF factory is the initial baseline, then the definition of a conceptual layout mirroring a flexible facility is followed, concluding with the definition of the final facility design that maximizes the output, the machines utilization and the global competitiveness of this factory.

This dissertation will exclusively focus on phase one and two. Along this mentioned goals, the objective of this dissertation lies in supporting the decision process for what should be done in the manufacturing system of IKEA Industry of Paços de Ferreira.

1.4 Approach

To tackle the shortcomings of traditional layout methods, an extensive review was made on the matter of manufacturing facility layouts and henceforward on manufacturing flexibility. Afterwards, according to the findings of the aforementioned literature review, the methodology for controlling the consequences of demand variability in the design of manufacturing systems will be developed and applied to the case study of IKEA Industry of Paços de Ferreira.

Several scenarios will be produced iteratively and evaluated in a way that allows the project team to better understand the manufacturing system and the necessary interventions of each of the alternatives.

It should be mentioned that the company has, previously to this dissertation, produced a simulation model of the manufacturing system in SIMIO, which will be used in this current project to inspect the system. Further informations of the correspondent model can be found on appendix A.

1.5 Structure of dissertation

This dissertation is composed by a total of six chapters. An introductory chapter, the present one, presents the dissertation, the field of work, its motivation, objectives and goals. A literature review follows to give insights on manufacturing flexibility, presenting existing solutions of flexibility integrations in production systems, as well as, analytical methods to tackle flexibility facility layout design and strategic implementation of flexibility. The chapter finishes with a brief presentation of the field of simulation. Afterwards, the proposed methodology for controlling the consequences of demand variability in the design of manufacturing systems is introduced and described. Following this chapter, a detailed presentation of the case study is develop, as well as, a review and assessment of the circumstances of this company. Then, the methodology is applied to the case study and several explored scenarios are presented. Finally, the dissertation closes with a reflection of the main conclusions, as well as, the presentation and identification of future research issues.

Chapter 2

Theoretical background on flexibility

In a time of great uncertainty in demand, flexibility is now becoming a fundamental approach to systems design [25]. For the past years, many scientific contributions highlighted this subject, both at industrial and academic level [21]. Designs that do not account for a range of possible future scenarios, risk major losses and significant unexploited value, over its life cycle [25].

The literature on the topic is vast, with major researches commented to the analysis of flexibility as a solution to cope with uncertainty [21]. However the link between flexibility and design is still weak [25]. Although it demonstrates great promise, the procedures for creating effective flexibility in design are not well established [25].

Developments and approaches from concepts, needs and dimensions to implementation and management aspects [11], [21] characterize the scientific contributions on the topic.

In order to effectively review the literature, a 3-Steps approach was followed, as represented on figure 2.1.

With resource to Scopus and Google Scholar databases, a search was firstly carried using a set of various keywords, here presented on table 2.1. The results were then analyzed with respect to abstract, introduction and conclusion. When valuable documents were found, the reference was kept to continue to the following step. A comprehensive analysis, then took place for all kept documents. Once again, when higher quality documents were found, the reference was marked and stored. The process concluded with a extensive research for publications that cited the highest quality articles in order to find more recent work based on these foundations.

State-of-the-art articles, taxonomies, conceptual frameworks, and reviews of the latest scientific contributions, at the time of the writing, all on the topic of manufacturing flexibility, served as the primary reference for gathering the highest quality literature.

Figure 2.1: Literature review research approach

Table 2.1: Literature search keywords set

Search Keywords Set on flexibility			
Manufacturing flexibility	Flexibility design	Manufacturing systems	State of art
Engineering design	Flexibility review	Discrete-event simulation	Facility layout
Design methods	Layout configurations	Flexibility implementation	

This chapter will continue with a review of the state-of-the-art on the literature of manufacturing flexibility.

2.1 Global overview of the manufacturing flexibility literature

Despite the general agreement about the relevance and benefits of manufacturing flexibility as one of the most important success factors for coping with uncertainties, research in manufacturing flexibility can, to some extent, be considered fragmented and unstructured [27].

Developments of the mater established over an explosion of empirical researches on a wide variety of topics [28], with limited presence of theoretical frameworks [27] and high ambiguity in the terminology used to refer to the multidimensional nature of flexibility itself [20], can be the cause of such scenario. [2] As a matter of fact, over 50 overlapping flexibility types haven risen from manufacturing research literature, since the interest on the field started. [27]

The literature does not clearly bring order and clarity to the academic field, with major penalties of misunderstanding and distrust the benefits of manufacturing flexibility. [2]

In late 2017, [2] distinguished 7 different clusters of researches in this highly dynamic field and characterized then in four distinct quadrants of a strategic matrix by its different levels of development. The result of this systematic literature review can be seen on figure 2.2.

Motor clusters, as the cornerstones of this discipline, will be the focus on this dissertation. Integrating Performance and Simulation research clusters of this quadrant, aligning the scientific contribution of strategist flexibility design and simulation tools development will be the fundamental bases of work.

2.2 Manufacturing flexibility

2.2.1 Manufacturing flexibility concept

An early definition of manufacturing flexibility is provided by [39] who credit [40] as having defined it as "the ability of a manufacturing system to cope with changing circumstances or instability caused by the environment". [14]

Adopting another view, [41] defined flexibility as "the ability of a manufacturing system to respond cost effectively and rapidly to changing product needs and requirements". [14]

Additionally [17] further extended the definition given by [42], in which flexibility was defined as the "ability of manufacturing function to react to changes in its environment without significant

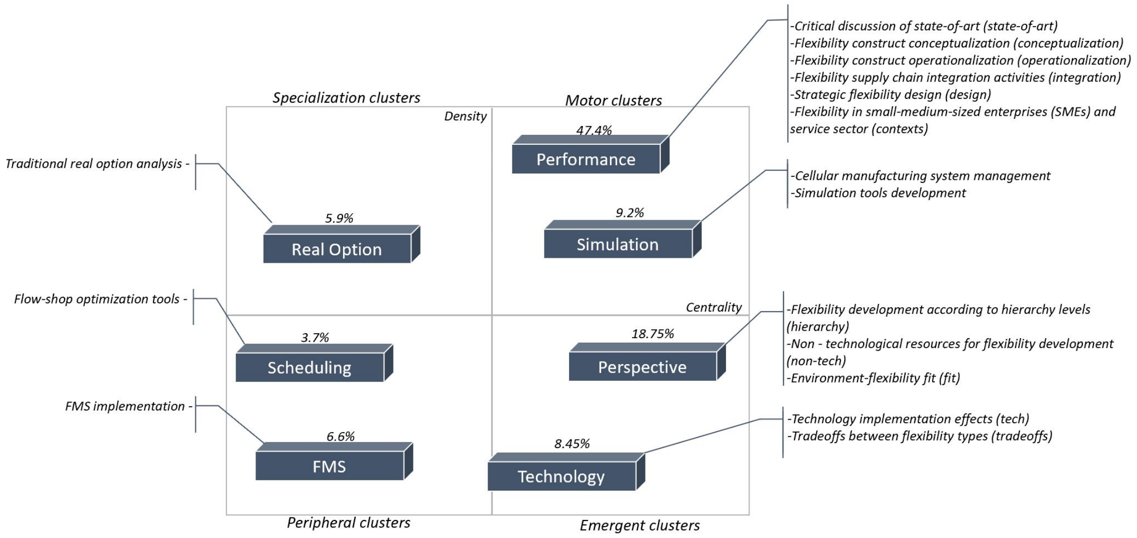


Figure 2.2: Strategic matrix and research lines within manufacturing flexibility clusters (source: [2])

sacrifices to firm performance", to become, the ability of a manufacturing function to make adjustments needed to react to environmental changes without significant sacrifices to firm performance, in with such adjustments were typically in the range of outputs and/or the mobility. [11]

Perhaps a more comprehensive definition of flexibility might be "the ability of a system to change or react with low penalty in time, effort, cost or performance" given by [30]. [14]

Different perspectives of flexibility concepts also endure in literature. As a example, [43] proposed that flexibility would be looked in two different perspectives, the short and long term. In the short run, flexibility should present it self as the ability of the system to adapt to changing conditions using the existing set and amount of resources. In the long run, it would measure the ability to introduce new products, new resources and production methods, and to integrate these into the existing production system. [11]

Further views can be seen in order to employ, implement and manage flexibility strategically. From a adaptive view, manufacturing flexibility can be perceived as a general ability to adapt and change to accommodate both internal as external uncertainties faced by a organization. From a proactive view flexibility is seen as system ability to cope with a wide range of possible environmental changes, allowing the companies to redefine market uncertainties or influence what costumer have come to expect from a particular industry. [5, 11, 44]

The dynamic and changing characteristic of manufacturing flexibility also engender a deeper understanding of actual and potential degree of flexibility installed on manufacturing systems. Potential flexibility characterizes the degree of flexibility which managers and operators believe the system could achieve and, in turn, actual flexibility represents the degree of flexibility which the plant is currently achieving. [11, 42] This feature is particularly linked to flexible, in view of the fact that, in opposition to a fixed design, completely unchangeable over its lifetime, flexible designs are intended to change over time. Indeed, the whole point of a flexible design is to enable management to respond pro actively to circumstances as they evolve. [25]

Manufacturing flexibility as the multi-dimensional concept that it is, can still be perceived, in a global overview, as a combination of multiple enablers, such as, company corporative culture, management structure, process technology, facility layout, information systems, and others. [14]

Whilst by no means exhaustive or particular comprehensive, the above definitions reflect the diversity of definitions and views present in the literature.

Although no general agreement exists, manufacturing flexibility is still clearly defined as the ability of a manufacturing system to respond effectively and efficiently to internal and external environmental uncertainties, in order to produce reasonably priced products. Effectiveness here representing the ability of the system to meet product variety requirements of right quality, quantity and at right time, and efficiency referring to a optimal use of all system resources. [11]

2.2.2 Taxonomies and conceptual frameworks

The classification of existing flexibility dimensions through taxonomies and conceptual frameworks, underline multiple divergent classifications, over the years. [21]

One of the most cited frameworks of the literature can be attributed to [3] who, in an attempt to survey the vast scientific contributions on flexibility until the moment of the correspondent article, extended [45] 8 dimension classification of flexibility to a 11 dimension classification. [14] The selected dimensions were group in a three levels degree classification and the associated interrelationships represented on a integrated framework, here exhibit on figure 2.3.

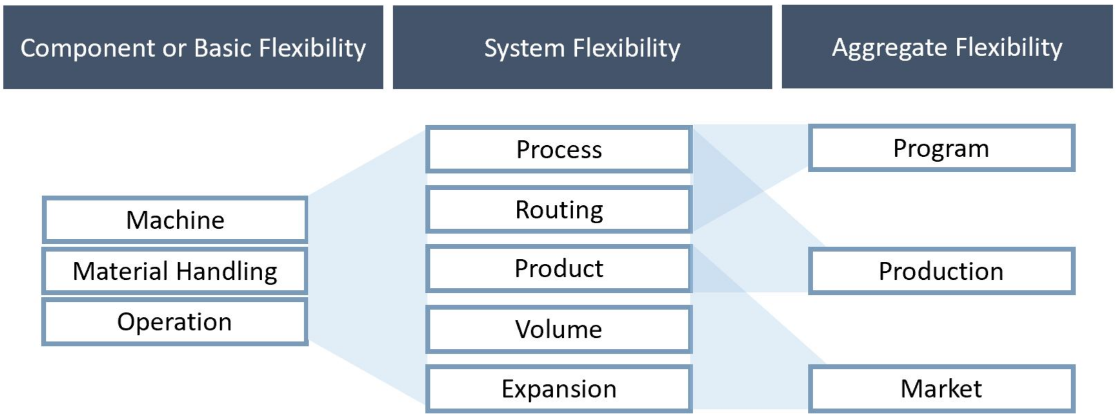


Figure 2.3: Linkages between the various flexibilities (adapted from: [3])

The classification and definition given to the 11 dimensions of flexibility by [3] are further explored on table 2.2.

In an attempt to validate the proposed framework of [3], [46] carried out a empirical research over 269 companies and developed an instrument to measure and analyze there flexibility. The study revealed that the 11 dimension classification of flexibility could be reduced to only 9 forms: Machine, Material-handling, Process, Routing, Volume, Program, Product & Production, Market and Expansion & Market flexibility. Additionally, by examining the relationship among business

Table 2.2: Flexibility levels and their definitions by [3]

Level	Flexibility Dimension	Definition
Elementary	1. Machine	Ability of a machine to perform the various types of operations without requiring a prohibitive effort in switching from one operation to another
	2. Material handling	Ability to move different part types efficiently for proper positioning and processing through the manufacturing facilities it serves
	3. Operational	Ability to produce a part in different ways
System	4. Process	Ability of a system to produce a set of part types without major setups
	5. Routing	Ability of a manufacturing system to produce a part by alternate routes through the system
	6. Product	Ability of the system to add or substitute new parts for existing part
	7. Volume	Ability of a manufacturing system to operate profitably at different overall output levels
	8. Expansion	Ease with which the capacity and capability of a manufacturing system can be increased when needed
Aggregate	9. Program	Ability of the system to run virtually untended for a long period
	10. Production	Ability of the system to produce a universe of part types without adding major capital equipment
	11. Market	Ability of the manufacturing system to adapt to a changing market environment

strategy, manufacturing flexibility and performance, they concluded that business strategy impacts on manufacturing flexibility that in turn impacts on organizational performance. [21]

In an attempt to understand the complex concept of flexibility, also [42] proposed a framework and a theoretical foundation for the development of generalizable measures for manufacturing flexibility. They identified 10 flexibility dimensions, similar to [3] classification, and organized them into four different manufacturing flexibility levels, individual resource level, shop floor level, plant level and functional level.

Other contributions like [4], also provided insights on different relationships among manufacturing flexibility concepts. The research theoretical model of [4] linked flexible manufacturing competencies with volume flexibility and mix flexibility, and with customer satisfaction. The analysis developed across a large number of organizations confirmed empirically that flexible manufacturing competencies support the flexible capabilities of the firm, which in turn enhance customer satisfaction, as represented in figure 2.4. [21]

The literature on taxonomies and conceptual framework evidence the importance of systematizing the knowledge concerning all provided flexibility forms regarding classification and characterization [21].

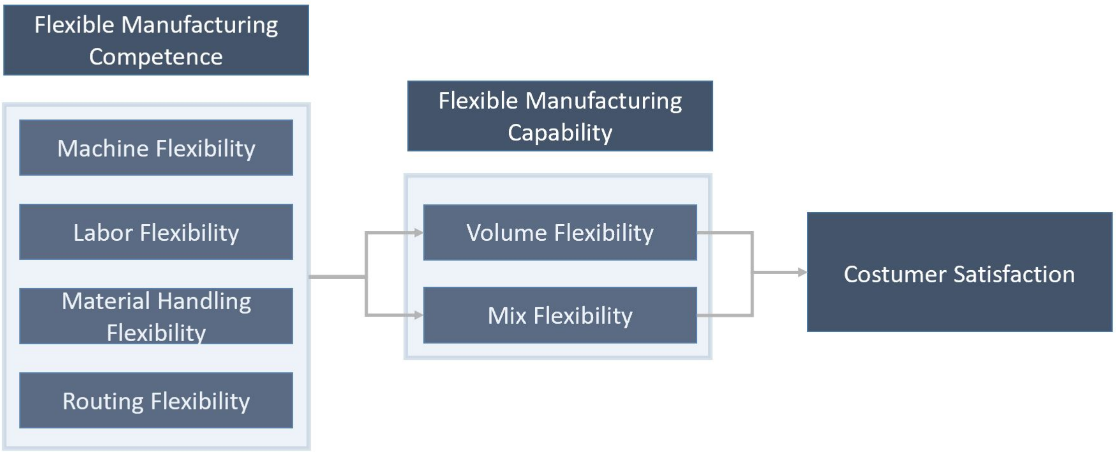


Figure 2.4: Linkages between flexible manufacturing competencies, volume flexibility and mix flexibility (source: [4])

It is clear that taxonomies and conceptual framework too surrounded themselves of divergences underlying the dimensions of flexibilities and no general agreement resulted of the numerous contribution on the literature, nevertheless much similarities exist between classifications.

2.2.3 Manufacturing flexibility dimensions

In order to understand each of the dimensions of flexibility, their value and application, the work and framework of [3] was use as a reference for further analysis. For each of the 11 dimensions, a brief summary of their use purpose, operational, as well as, strategic, and the means to obtain them, will be presented following [3] definitions. While the purpose of a flexibility dimension express why it is needed, the **means to achieve** refer to the firm's technological and managerial response to that need [3].

Machine flexibility At its own level, machine flexibility allows lower batch sizes that lead to savings in inventory costs, higher machine utilizations, production of complex parts, shorter lead times for new product introductions, and better product quality realizations in the face of random variations in input quality.

Means to achieve Multipurpose, multi-axis adaptable machines installed in a way that avoid physical limitations that can inhibit changes.

Material handling flexibility Having a flexible material handling system increases availability of machines and thus their utilization and reduces throughput times.

Means to achieve Transporting devices and appropriate layout design. On highly automated facilities, devices such as automated guided vehicles, robots, and computer control, which can send parts to new paths in cases of blocking and machine breakdowns should be used.

Operational flexibility Operation flexibility of a process allows for easier scheduling of parts in real time and increases machine availability and utilization, especially when machines are unreliable.

Means to achieve Operation flexibility of a part derives from its design. The design should allow easy access for various operations. Parts that are assembled from standardized components or parts that are modular are likely to exhibit operation flexibility. Systems such as CAD/CAM, computer-aided process planning (CAPP), and group technology make it easier to design parts possessing operation flexibility.

Process flexibility The main purpose of process flexibility is to reduce batch sizes and reduce inventory costs, even when there are shifts in the product mix demanded by the market.

Means to achieve Multiskilled workers who can handle different products and the ability to transfer a variety of fixtures and tooling into and out of the system enhance process flexibility.

Routing Routing flexibility allows for efficient scheduling of parts by better balancing of machine loads. Furthermore, it allows the system to continue producing a given set of part types, perhaps at a reduced rate, when unanticipated events such as machine breakdowns, late receipt of tools, a preemptive order of parts, or the discovery of a defective part occur. Thus, it contributes toward the strategic need of meeting customer delivery times. Routing flexibility also facilitates capacity expansion if needed.

Means to achieve Multipurpose machines, machines with overlapping process envelopes, pooling of identical machines into machine groups, system control software, versatility of material handling system, and operation flexibility of parts. Some planned underutilization of machines (or, redundancy in machines) is needed in order for the system to be able to be reschedule and maintain the overall production rate in case of a machine breakdown.

Product Product flexibility allows the company to be responsive to the market by enabling it to bring newly designed products quickly to the market.

Means to achieve Layout that manufacture products assembled from standardized parts differentiated only in the later stages of its production. Product flexibility depends also on machine flexibility, material handling flexibility, operation flexibility, efficient CAD/CAM interface, CAPP, group technology organization, use of similar part programming routines, rapid exchange of tool and dies, flexible fixtures.

Volume Volume flexibility permits the factory to adjust production upwards or downwards within wide limits. Successful companies in cyclic industries like furniture often exhibit this trait. According, volume flexibility has two aspects: speed of response and range of variations. Volume flexibility serves survival strategies such as maintaining existing markets and profitability.

Means to achieve Can be achieved in several ways. Excess modular capacity that remains unused except after breakdown occurs, the high capacity facilitates a quick return to normal production and in-process inventory levels. Subcontracting network. JIT approach for volume flexibility and/or redistribution of workers assigned elsewhere when production volume decreases.

Expansion Expansion flexibility is important for firms with growth strategies such as venturing into new markets, since it permits step-by-step adaptation of the system for expansion. Expansion flexibility helps to reduce implementation time and cost for new products, variations of existing products, or added capacity.

Means to achieve Can be achieved in several ways. Building small production units, having modular flexible manufacturing cells, having multipurpose machinery that does not require special foundation and a material handling system that can be more easily routed, having a high level of automation that can facilitate mounting additional shifts, providing infrastructure to support growth, and planning for change.

Program Program flexibility reduces throughput time by having reduced setup times, improved inspection and gauging, and better fixtures and tools. It allows simultaneous improvements on productivity and quality.

Means to achieve Program flexibility depends on process and routing flexibilities and on having sensors and computer controls for detection and handling of unanticipated problems such as tool breakages, part flow jams, etc. Quality control and tool maintenance.

Production Production flexibility allows the firm to compete in a market where new products are frequently demanded. Production flexibility minimizes the implementation time for new products or major modifications of existing products. On the operational level, it permits an increase of part families and allows the firm to diversify its risk.

Means to achieve Production flexibility depends on the variety and the versatility of the machines that are available, the flexibility of the material handling system in use, and the factory information and control system. Thus, the production flexibility derives from the capability of aggregation of the flexibilities of the machines and material handling systems. Production flexibility is related to the properties of the transportation system, warehousing system, interfacing system, distributed data bases, systems control, and software modularity. An open communication system as well as the use of a common communication protocol will help to increase production flexibility.

Market Market flexibility is important for a firm's survival in environments that are constantly in flux. Market flexibility allows the firm to respond to these changes without seriously jeopardizing the business. It is essential if the firm's market strategy emphasizes customized products and frequent product changes.

Means to achieve Product, volume, and expansion flexibilities contribute to market flexibility, as the manufacturing system may be required to process new products, cope with fluctuating production volumes, and even to undergo capacity changes. Market flexibility requires that the process of production planning and inventory controls be closely integrated with such marketing functions as market forecasts, product development, and customer relations. Moreover, good relationship with suppliers and well developed distribution channels are also essential for market flexibility.

For further information see [3].

2.2.4 Environmental uncertainties in manufacturing systems

Inevitably all manufacturing systems, throughout their life cycle, will have at some point to handle change, whether it is planned or not. Unplanned changes are those which occur independently of the system's intentions but to which it has to respond and planned changes happen as a result of some conscious managerial action which is intended to alter some aspect of the system or its relationship with the environment [11, 47].

In [9], changes are characterized as the environmental uncertainties of the system. Having classified then into internal and external changes the author defined thus internal uncertainties as the ones that occur within an organization, such as equipment breakdown, variable task times, queuing delays, rejects and reworks, manpower changes, material shortages, resource acquisitions, and external uncertainties as that ones that occur outside the organization, such as **changes/fluctuation in the level of demand**, product price changes, **product mix changes**, technological changes, macro-economic policies, social as well as political uncertainty and action of competitors. [11]

Throughout the years, uncertainty dimensions have been classified into various others categories in order to perceive the meaning of uncertainty, nevertheless the viewpoint originated with [48] that uncertainty emerge from internal and external causes still mostly remains. [9]

Another example of this fact is the work presented by [5], where seven distinct dimensions of environmental uncertainty were categorized in internal or external uncertainties. Uncertainty of market acceptance of a kind of product, product life cycle, product specifications and aggregate demands were classified as external uncertainties originating from market and product needs. Uncertainty of machine breakdown and material characteristics were classified as internal uncertainty, coming from the interior operations of manufacturing and purchasing in the company. The final uncertainty dimension was then presented as the realization of possible changes happening to the six uncertainty dimensions already mentioned. Moreover, in order to understand the relationship between manufacturing flexibility and this environmental uncertainty, the author proposed the following relationship, here presented on figure 2.5. Based on this work, [49] extended the environmental uncertainties of [5] to include also the uncertainty of product development. [9]

Whilst by no means exhaustive, the above definitions reflect once again the diversity of definitions and views present in the literature on environmental uncertainties.

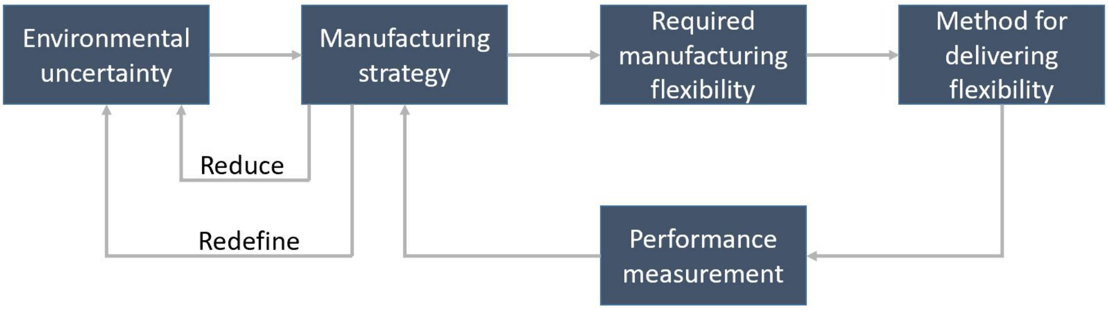


Figure 2.5: Conceptual framework of the relationship between environmental uncertainty, manufacturing strategy, and manufacturing flexibility (source: [5])

Although no clear agreement exists when it comes to characterize and enumerate environmental uncertainties, based on several scientific contributions, the existing environmental uncertainty dimensions were compiled an are now presented on table 2.3 to serve as further reference in this dissertation.

Table 2.3: Uncertainty dimensions (adapted from: [5, 9–11])

Uncertainty	Definition of uncertainty	Environmental uncertainty factors
Internal uncertainties	Occur within an organization	1. Machine breakdown 2. Transport breakdown 3. Variable task times 4. Queuing delays 5. Rejections and Reworks 6. Material shortages 7. Manpower changes, variations on absenteeism 8. Resources available
External uncertainties	Occur outside the organization	9. Changes/fluctuation in the level of demand 10. Product price changes 11. Product mix changes 12. Product design changes 13. Technological changes 14. Macro-economic policies 15. Socio political changes 16. Competitors actions 17. Supplier disturbances

2.2.5 Relationship between environmental uncertainties and manufacturing flexibility dimensions

On the matter of manufacturing flexibility there are those who think that a relation between flexibility dimensions and uncertainty can be correlated. In fact, various scientific contributions have been supporting this reasoning [9, 50].

The research framework proposed by [9], in accordance with [50] on flexibility competence and capability, characterized internal and external flexibilities of an organization in relation to the internal and external environmental uncertainties. External flexibilities are those that affect the competitiveness of a company, and internal flexibilities are the ones who improve the performance of a system. A qualitative elaboration of the relationship between the dimensions of flexibility and the environmental uncertainties is given on table 2.4, in agreement with this study, to serve also as further reference in this dissertation. [9]

Table 2.4: Environmental uncertainties and flexibility needs (adapted from: [9])

	Environment uncertainties	Flexibility needs
Internal	Machine breakdown, Transport breakdown, Variable task times, Queuing delays, Rejections and Reworks, Material shortages, Manpower changes, variations on absenteeism, Resources available	Flexibility that the system needs includes machine flexibility, material handling flexibility, routing flexibility, operational flexibility and/or process flexibility.
External	Changes/fluctuation in the level of demand, Product price changes, Product mix changes, Product design changes, Technological changes, Macro-economic policies, Socio political changes, Competitors actions, Supplier disturbances	Required flexibilities are considered as a chain connection between corporation strategy, marketing strategy and manufacturing strategy. Needs production flexibility, volume flexibility, delivery flexibility and/or expansion flexibility

2.3 Strategic flexibility design

Strategist flexibility design is all about creation, development and implementation of strategic alternatives that in turn lead to a positive competitive differentiation. [51]

The central focus of this work lies exclusively on manufacturing facility layouts design and for this reason, all further discussions will target uniquely this subject.

It is clear that facility layouts exhibit extensive impact upon the effectiveness and efficiency of a manufacturing system. [12, 52] For this reason, there is a tremendous opportunity to achieve further competitive advantage with an improved layout design.

In literature, layout flexibility is still not much explored and very little exist on the matter [18], nonetheless multiple options and trends started to emerge over the years in order to deal with dynamic and stochastic environments. [12]

2.3.1 Facility layout design approaches in dynamic environments

Considering current approaches to design facility layouts in dynamic environments, two distinct categories can be featured, in agreement with the already debated [1] scientific contribution. [12]

Robust design Characterized by a facility layout robust enough to handle multiple production periods or scenarios.

Flexible design Characterized by a facility layout flexible or modular enough to be reconfigured with minimal effort to meet changing production requirements.

The robust design approach requires the assumption that either the production data for multiple periods is available at the initial design stage itself so that, a thoughtful identification of layout characteristic conferring robust solutions, over the multiple periods, can be studied, or that developing a layout with inherent features, as for duplication of key resources at strategic locations within the plant, will ensure reasonable efficiency of the manufacturing system through various production periods. The first assumption suffers from the fact that production data must be available at the initial stage of the project, which is unlikely in a dynamic environment. Designing features that allow future flexibility is much more promising, as refereed in the second assumption, however, research in this area remains limited. [12]

The flexible design approach on the other hand, assumes that layouts would be reconfigured after each period and should be designed to minimize reconfiguration cost while guaranteeing reasonable efficiency of the manufacturing system in each period. To carry out this balancing, knowledge of production, for all future periods, would be again necessary. An alternative to this reality is designing reconfigurable features into the layout so that re-layout costs are always minimal. Such as for flexible layouts, research on reconfigurable layouts is still limited. [12]

In view of the above stated, it is possible to identify four types of distinct layouts. Depending upon the degree of uncertainty of future production requirements and the strategic view of the company to employ or not large alterations in its manufacturing system, correlated naturally with the associated costs of re-layout of each alternative, the four layouts types can be employed as illustrated in table 2.5. [12]

Table 2.5: Classification of factory layout for dynamic environments (source: [12])

	Uncertainty of Future Production Requirements		
Cost of re-layout	Low	High	Design Category
Low	Dynamic layout	Reconfigurable layout	Flexible design
High	Robust layout	Distributed layout	Robust design

In a dynamic layout the main objectives are to identify a layout configuration in which both material handling and re-layout costs are minimized over the planning horizon. In a robust layout the main objectives are to determine the proper configurations that will perform suitably under multiple production demands, considering typically a optimistic, pessimistic, and most likely scenario. In a distributed layout, the main objectives are to use duplication and disaggregation of existing functional departments to determine proper configurations and the best suitable locations for resources. In a reconfigurable layout the main objectives are to promote fast changes and adjustments in order to further compensate variation of demand variability. [12]

The dynamic and the robust layout assume that production data for future periods/scenarios are available and consider the costs of switching from one period to the next [53, 54]. These assumptions may turn the layout problem easier to solve, but are unrealistic in many situations. That is because changes in production requirements usually are unexpected or only known slightly ahead of the next production cycle initiation [55]. This way, the approaches that considered low uncertainty in demand, as it is the case for dynamic and robust layouts, have the shortcoming of being deeply subjective to the accuracy of forecasts. As for the distributed and reconfigurable layouts, even in the absence of reliable information, the systems will mostly maintain sufficient levels of efficiency [18]. [12]

In today's environment with companies becoming increasingly vulnerable to uncertainties in demand, subjected to unavoidable forecasting inaccuracies and with the clear necessity for flexible designs, reconfigurable layouts, with its flexible design, present the suitable solution for current necessities. Accordingly, a reconfigurable layout is capable to rearrange frequently, in order to adjust its configuration to new circumstances, with minimal effort, providing the exact capacity and functionality needed, when required and considering for that its system operational performance. It assumes that production data are available only for the current and upcoming production period and evaluates the system operational performance achieved. [55]

Not all type of industries are subjected to such extreme realities and for this reason the choice of design and respective layout will need to be studied and adapted to each particular case. In the end, the type of industry, the company strategy, the current situation of the company and future perspectives and equally the associated environmental uncertainties and the manufacturing environment will mostly dictate what will be the best choice for the manufacturing system.

2.3.2 Flexible facility layout design

Flexibility is one of the most important parameters to facility layout design. It provides the capacity needed to produce diverse products in the same system and allows layout reconfigurations, with minimal effort, to meet changes in production requirements, combating high levels of uncertainty. [55] Following the definition of [56], layout flexibility can be seen as the ability of a layout to respond to known and future product mixes.

Along the years several strategies were developed to apply some degree of flexibility into manufacturing systems. The approaches consisted in installing multi-purpose stations, using parallel assembly lines, reducing the set-up time at installed equipment, and so on. [11]

Selecting the necessary flexibility dimensions and designing a flexible layout can be a complex task. With the aim of combining production flexibility and productivity, the design decisions of a flexible manufacturing system must be based on system performance, defends [57]. Notwithstanding, current literature on such mater still does not provide enough detailed to analyze system performance in a flexible system with different layout configurations.

In [57] work, discrete-event simulation models are presented as a suitable tool to design this production systems and investigate the effectiveness and efficiency of the flexible design, considering for this, system performance metrics, such as, manufacturing lead time, bottleneck analysis, throughput, resource utilization, inventory and queue levels, set up times, and number of workstations. Fundamentally, an efficient manufacturing system demonstrates the ability of the layout design to better perform and handle changing requirements more effectively [58, 59]. Therefore, the efficiency of an entire manufacturing system can be a strong indicator of the systems performance in terms of flexibility. [60]

Flexible facility layouts design are critical to ensure the successful fulfillment of demand variability. [61]

Further discussions on utilization of discrete event simulation in the design process of flexible systems can be found in section 2.5.1 of the current chapter.

2.3.3 A strategic approach towards flexibility

In order to strategically achieve a successful flexible facility, not only incorporating physical resources are necessary but, in fact, a trade off between physical resources and operations strategies is needed. The author of [6] defends that the various dimensions of manufacturing system flexibility, viewed as physical and logical manufacturing system re-configuration methods, should be employed together to achieve better flexibility and agility. In figure 2.6 it is possible to view their representation on such matter.

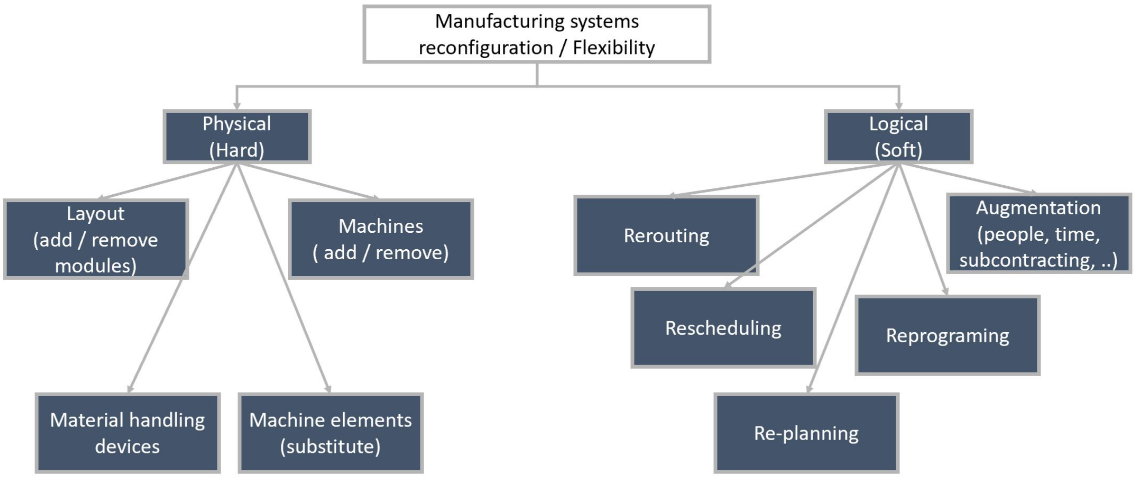
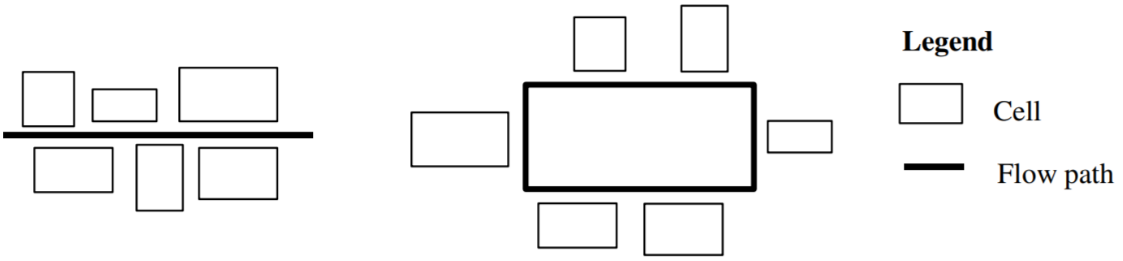


Figure 2.6: Manufacturing system reconfiguration (source: [6])

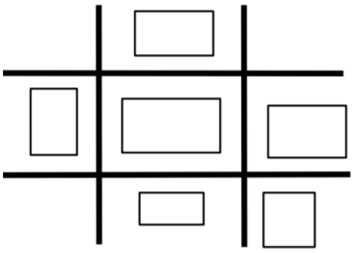
2.3.4 Flexible manufacturing systems configuration

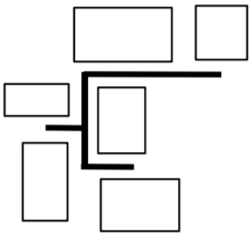
The configuration of the manufacturing system layout and the respected material flow path also play an important role in flexible facilities, as this interaction will enable easy modifications to respond to changes in demand, product mix or job priorities. [7]

In [7], four basic flexible layout configurations were defined as spine, circular, ladder, and open-field, which can be viewed in figure 2.7. The design of the respective flow path in a flexible layout configuration results, frequently, as one can see, in a directed material flow [62].



(a) spine layout (b) circular layout





(c) ladder layout (d) open-field layout

Figure 2.7: Flexible manufacturing systems configurations (source: [7])

The interaction between the layout and flow path in this type of system design is a critical mater, since it is also known that, 30 to 75% of the total costs of production can be attributed to materials handling and layouts [63].

2.4 Strategic implementation of flexibility

It is imperative that firms identify the right flexibility dimension for their manufacturing flexibility as 40% of flexibility improvement efforts are unsuccessful due to failure in identifying precisely what kind of manufacturing flexibility is needed, how to measure it and which factors must affect them [26].

Manufacturing flexibility must be carefully justified, planned and managed in order for its potential benefits to be fully realized [11]. Flexibility that cannot be implemented when needed has too little value [25].

Managers will not implement all required flexibility dimensions and levels at once, and therefore the required flexibility types must be prioritized and ranked. This is also needed to help design, justify, implement and maintain the specific organizational and technological tools (FMS, employees with broad skills, versatile machine tools and flexible facility layout) necessary to achieve the required manufacturing flexibility [11].

The implementation phase for any design flexibility may last years, often a decade or more, so it is necessary to be aware of the common obstacles of implementation and what actions could be followed to tackle them. In the next sections the common obstacles to a implementation and the preventive and operational actions to tackle them are presented. [25]

2.4.1 Common obstacles to implementation

When implementing a project that aims flexibility integration, [25] enumerates five common obstacles that may jeopardize a successful outcome.

Ignorance Future managers may forget, not even know about or otherwise ignore that flexibility exists.

Inattention No monitoring exist to the circumstances that would trigger the appropriate use of the flexibility, and managers miss good opportunities to use this asset.

Failure to plan The design process may fail to think through what is needed to be done when implementing flexibility, and thus create insurmountable obstacles.

Stakeholder block Groups using or affected by the system may mistrust flexibility and manage to block there use.

External developments Regulatory, political, or other developments may eliminate or otherwise constrain the right to implement the flexibility.

2.4.2 Preventive and operational actions to tackle implementation obstacles

As defended by [25], to maximize the likelihood of being able to implement design flexibility, the design process can take both initial preventive and ongoing operational actions. The former leads to the latter. [25] points out the following actions:

Preventive actions

Integrated project delivery Creating the design with the participation of major stakeholders in the process, thereby uncovering and understanding many of the issues that might eventually be barriers to implementation.

Development of game plan Carefully thinking through what would be required for future implementation, for each of the flexibility dimensions, avoiding the creation of obstacles while laying the groundwork for easy implementation.

Preparatory action In accord with the game plan, taking actions that increase the potential for implementing the flexibility, should it ever be desirable.

Operational actions

Maintaining the right to implement Because the ability to implement is often contingent on various legal permissions, it is important to keep these up-to-date and in effect.

Maintaining the knowledge to implement Effective implementation requires people, and more generally institutions, to understand the nature of the flexibility and know how to proceed when the opportunity is attractive.

Monitoring the environment This is crucial to know when it would be desirable to implement flexibility and to obtain its highest value.

To have a good implementation of flexibility, secure and provide the appropriate informations as long as the manufacturing system requires flexibility is crucial. Ensure a strong flow of information may not always be easy and no general method exists to do so, as different approaches may be better in different organizations. A possible solution, that already achieved incredible outcomes, passed by setting up, in the concerning organization, a fix team to manage the implementation, as well as, all processes related to flexibility [25].

2.4.3 Methods by which the need for flexibility will be reduced

It's true that flexibility displays itself as an excellent solution to manage uncertainty and demand variability, nonetheless in some situations it can be beneficial to reduce the degree of flexibility necessary to install in a manufacturing system with the benefit of reducing investments in flexibility and the environmental uncertainties itself. [11,25,61]

Ettlie and Penner-Hahn [64] stated that if the firms knew their markets better they wouldn't need as much flexibility. In fact a better knowledge of product features, expected demand, anticipated product life-cycles and competitor's strategies, could, to some extent, reduce the magnitude of the flexibility required. [11]

Modular designs, inventory and focusing plants are known to reduce the extent of the necessity of flexibility integration [30], and products and processes characteristics are related to reduce the effects of both external and internal uncertainty. [65] Indeed, companies that mass-produce a narrow range of products may reduce internal uncertainty and limit the amount of external uncertainty by using dedicated technology, centralized infrastructures and buffers before and after the process. Conversely, companies processing a wide range of products and volumes can use flexible technology and a decentralized infrastructure to accommodate the effects of external uncertainty and internal buffers to limit internal uncertainty. [11]

Controlling techniques can also be use by management to limit the amount of uncertainty the system experiences, [22] categorized such methods as monitoring and forecasting, coordinating and integrating, focusing and confining, delegating and subcontracting, hedging and substituting, negotiating, advertising and promoting, maintaining, updating and training. [11]

Such methods, although beneficial and essential to any company, will not resolute entirely the necessity for flexibility integration. [25]

2.5 Simulation tools development

As a powerful tool for analyzing complex stochastic systems, simulation in manufacturing is gaining increased attention. Having proven its incredible value in several successful applications in the manufacturing sector, simulation stood out when evaluating the design and operational performance of a manufacturing system. [61, 66, 67]

As a key technology to support the manufacturing system design, a indispensable problem solving methodology's, used to describe and analyze the behavior of production systems, ask what-if questions and aid in the design of future ones, simulation present itself as a excellent modeling alternative to determine a good layout. [67]

Flexible manufacturing systems problems can be in fact classified as design, planning, scheduling and control problems. The multidimensionality of flexible manufacturing systems design added to the complexity of this problems makes them beyond the reach of many analytical models and provides a suitable environment for application of simulation. [61]

As one of the most commonly used techniques for analyzing and understanding the dynamics of manufacturing systems, Discrete Event Simulation, is a great alternative for the manufacturing system design, enabling the evaluation of multiple options for system configurations and operation strategies and giving support to the decision making process. [61, 68]

2.5.1 Discrete event simulation

Discrete event simulation, as one of the many types and kinds of simulation, presents numerous successful cases published on various application areas as general system design and facility layouts, material handling systems designs, cellular manufacturing systems design, flexible manufacturing systems design, manufacturing operations planning and scheduling, maintenance operation planning and scheduling, real time control and operating policies. In each and every scientific contribution, the benefits which comes from experimenting with a model of a real system stayed fully reflected. Understanding the interdependent relationships naturally occurring in the complex manufacturing environment and quickly and accurately model modification without the necessity of making costly guesses have indeed showed its tremendous potential. [61, 66, 68]

Focusing on manufacturing system designs, discrete event simulation showed to be the appropriate tool to evaluate current layout facilities, see potential areas for improvement and evaluate different layout solutions [66]. Therefore, several researches have applied simulation in different facility layout problems, such as [69, 70].

Jithavech and Krishnan [71], as an example, presented a simulation-based method to develop an efficient layout design under uncertainty in product demand. In this study the impact of stochastic demand in terms of risk were quantified and it was showed that this method could significantly reduce the risk associated with the layout. [61]

Several other researches have already target specifically the use of simulation to address issues concerning the design of flexibility manufacturing systems. [61]

An approach to identify productive and counterproductive performance zones of an FMS was proposed by [72], that used a simulation model of a hypothetical manufacturing system to answer the question of whether an increase in flexibility would have the expected benefits and up to what level of flexibility could be expected improvements. [61]

In a different study, [73] analyzed routing policies and the effect of changing part mix ratios under both infinite and finite buffer capacity in an FMS, using simulation. [61]

Ozmutlu and Harmonosky [74] proposed a rerouting heuristic to minimize mean flow time in FMS, with consideration of machine failures, and the performance of this heuristic was tested via simulation. [61]

Indeed, a number of simulation studies have been conducted to deal, not only with cases of facility layout design but also flexible manufacturing systems design, making DES a well-known suitable option for this dissertation.

2.5.2 Application of simulation

Although simulation can be used widely, following the work of [66], here are the situations where it is most useful the application of discrete event simulations:

1. when there is no simple analytic model, spreadsheet model or "back of the envelope" calculation that is sufficiently accurate to analyze the situation;

2. when the real system is regularized and system components can be defined, characterized and their interaction defined;

3. when the real system has some level of complexity, interaction or interdependence between various components that makes it difficult or even impossible to predict the effect of proposed changes;

4. when in designing a new system there are considered major changes in the physical layout or operating rules or new and different demand compared to the existing system;

5. when it is considered a large investment on a new or existing system, hence facing a considerable risk;

6. when it is necessary a tool where involved personal can agree on a set of assumptions, and then see (both statistically and with animation) the results and effects of those assumptions;

7. when it is necessary to raise awareness, especially in systems of large physical scale, where the simulation animation may be the only way in which most participants can visualize how their work contributes to overall system success or may creating problems for others.

2.6 Research challenges

Manufacturing flexibility has been recognized as a vital competitive advantage [75], co-existent with cost, quality and time, but struggling in finding a common base for its definition [11], framework and application methods [26, 76].

The first challenge for flexibility integration is the identification of the appropriate enablers, this is the essential dimensions, and required level of flexibility needed for a manufacturing system to cope with uncertainty [77]. Researchers stressed that prioritizing flexibility dimension are extremely beneficial at this stage [3, 5]. Equally, developing a deep understanding of how the system responds to current uncertainties, and what this might be, are greatly recommended [25].

The second challenge for flexibility integration is how to incorporate flexibility on the design of manufacturing facilities. For now such topics are still not much explored [18]. In literature, as regard to this matter, recent trends started to emerge in the field of dynamic and stochastic environments, after the recognition that existing layout, designs and methods do not meet current needs with its deterministic and static views. At this stage, in order to identify and choose better designs that deliver the best performance under realistic conditions it is recommended to identify and explore opportunities for value-adding flexible design. This is a crucial paradigm for the design of systems under uncertainty. At this stage it will be important to keep in mind that design flexibility does not provide the best design under all considered circumstances instead flexibility in design aims to provide improved solutions overall [25]. In the end the choice of layout will mostly depend on the uncertainty with respect to future production requirements, the prioritized flexibility dimensions and the strategic view of the company to employ or not large alterations in its manufacturing system, correlated naturally with the associated costs of re-layout of each alternative.

The third challenge for flexibility implementation is how to strategically manage flexibility throughout the life cycle of the manufacturing system. Secure and provide the appropriate informations as long as the manufacturing system will require flexibility will be the key to a successful implementation [25].

Designing flexible plant layouts for manufacturing facilities where product demands and product mix are subjected to fluctuation will be sustained by the effectiveness of the final system design to cope with product demand variability. One of the best tools available to evaluate current layout facilities, see potential areas for improvement, evaluate different alternative layout solutions in stochastic environments assisting consequently in the first two challenge for flexibility implementation here refereed is DES [66, 68].

The expected approach to the design process of plant layouts in stochastic environments witch aims to control the consequences of demand variability in manufacturing systems will be, thus, in accordance to the findings of the stated literature review. In the following chapter, the developed approach is explained in detailed.

Chapter 3

Proposed methodology

This chapter presents the developed methodology to control the consequences of demand variability in the design of manufacturing systems. The approach was developed to reflect and support the reality of a manufacturing system, with its inevitable changing environment and changing objectives by, not only, supporting and enabling modifications but by sustaining a controlled and stable outcome.

It is ambitioned with this methodology to conserve and protect stable transitions, as well as, a continuous improvements.

The chapter will continue in the following way, firstly the methodology is described, then a detailed characterization of the approach is presented, finishing with the validation method used.

3.1 Proposed approach

3.1.1 General structure

Established to have a broad and generalized application for manufacturing system overall, this iterative and systematic method supports **controlled changes** in the design process of a manufacturing system. An efficient control of the consequences of variability entails a clear understanding and analysis of source variations, along with a clear identification of effective solutions and a controlled monitoring and adaptability towards the reality of a system, prerequisites of the methodology.

By targeting demand variability, it is ambitioned a design that controls the repercussions of change, accommodates environmental uncertainties without major necessities of extensive interventions, yet it is prepared to establish adjustments, throughout the life-cycle.

The developed methodology integrates a six-step cycle and its structure can be found in figure 3.1.

Three main phases frame this methodology: a strategic analysis; a operational analysis; and strategic implementation. The objective of this sequence is enabling a strategic design process, in which, each phase contributes to a specific facet of the methodology.

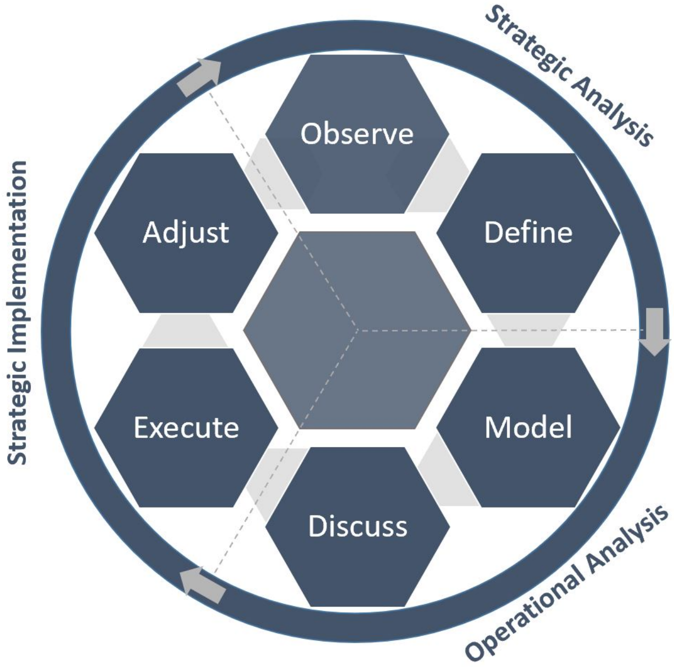


Figure 3.1: Proposed methodology

Strategic analysis As featured to map out current positions of a company, within internal and external environments, before the development of strategic plans for future directions and growth, a strategic analysis provides a primary evaluation of the system, characterizing the manufacturing system state and supporting the identification and definition of possible interventions.

Operational analysis As generally adopted to determine the efficiency of the various aspects of a business operation, aiming to determine whether each area of the organization is contributing effectively to the overall performance of the system, a operational analysis complements the initial strategic analysis and assists in the definition of the future layout design, by evaluating manufacturing system performances and efficiencies of current and potential design alterations.

Strategic implementation As conducted to promote executions of plans and strategies to reach desired goals, including interventions concerning organizational structures, key personnel actions, and control systems [78], a strategic implementation supports a efficient execution of the necessary interventions for the future layout design and assists potential adjustments to the refereed actions.

Integrating this particular frame and merging this three phases, enables the proposed objectives and functions of this methodology.

The characterization of this qualitative methodology is further described in figure 3.2. A detailed description of this steps and the recommended tools to be employed in each of then, are now further presented.

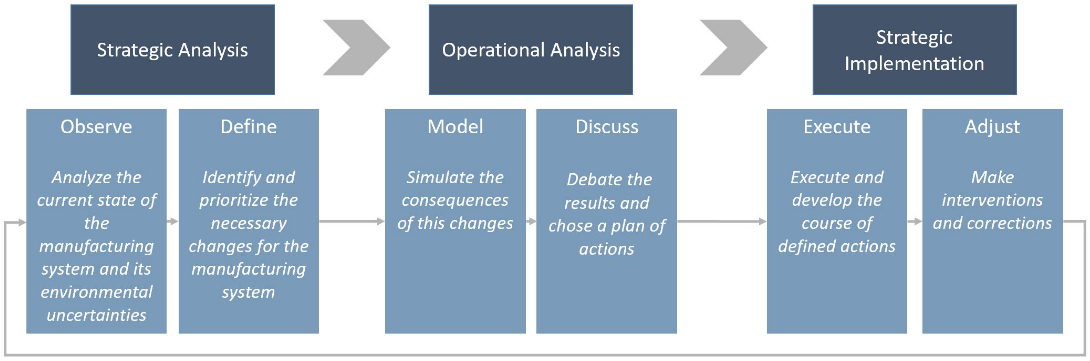


Figure 3.2: Methodology description adopted in this work

3.1.2 Observe

Each iteration of the methodology initiates with a period of observation. Exploration and evaluation of the manufacturing system state are the main goals of the present step. A deep analysis of the main opportunities of improvement in production and the determination of the current uncertainties within the system are required. Understanding the causes of the current inefficiencies, therefore, presents a vital contribution. Emphasizing routes and flow paths analysis is required.

Observation of the current manufacturing system is as necessary as analyzing past data. Demand variations and analysis of possible future trends and drivers is proposed in this step.

At this stage the analysis can be made by observations of the real manufacturing system, historic data analysis or meetings with personal.

3.1.2.1 Objectives

1. Analysis of possible future trends and drivers;

2. Determination of opportunities of improvement in production;

3. Recognition of major uncertainties of the system.

3.1.2.2 Tools and Techniques

- Ishikawa Diagram;

- AS-IS Sankey Diagram.

3.1.3 Define

The methodology continue with the definition of possible interventions in the system and the reflection of the required flexibility dimensions to tackle the uncertainties already identified. Prioritizing possible interventions, by importance and urgency, is necessary at this stage. Screening is therefore required to reduce the set of decisions that will be model and further studied in the next phase.

Definition of possible improvements for the layout and a development of a TO-BE analysis to each of the respective alternatives is recommended. Once again, emphasizing routes and flow paths analysis is required.

The *Strategic Analysis* phase is finished with the conclusion of this step.

3.1.3.1 Objectives

1. Identification of required flexibility dimensions;
2. Definition of possible interventions in the system;
3. Screening of alternatives.

3.1.3.2 Tools and Techniques

- TO-BE Sankey Diagram;
- *Environmental uncertainty and flexibility needs* table (chapter 2, table 2.4);
- Brainstorming;
- Rough-Cut Layouts.

3.1.4 Model

The methodology progresses with the initiation of a new phase, the *operational analysis*. Modeling and simulation of different interventions in the system are the required tasks for the present step.

Aiming to understand the consequences and impact of each alteration and ultimately support the definition of the future layout design, the evaluation of current and potential design alterations is required. Efficiency determination and comprehension of whether each area of the system is contributing effectively to the overall performance is equally crucial. Analyzing the behavior of the machines, buffers and flow paths, for future mix, and line design accordingly.

The analysis process is made by resorting to the simulation model of the manufacturing system. In this step, it stays latent the necessity of understanding the level of detail that requires to have the simulation model. This, along with the defined key performance indicators that assist in the evaluation and comparison of design possibilities, are key aspects in this step. Note that too much information on the simulator will negatively impact the time duration of the modeling and analysis phase. The target stays in achieving fast modulations and simulation.

3.1.4.1 Objectives

1. Modeling of the manufacturing system and correspondent interventions;
2. Dimension of resources in the manufacturing system;
3. Analysis of the impact of this changes.

3.1.4.2 Tools and Techniques

- Discrete event simulation;
- Dashboards;
- Key Performance Indicators (KPI).

3.1.5 Discuss

After simulating and model the alternatives, a step of thoughtfully deliberation is followed. Here the main objective is to choose the future layout design. Debating pros and cons of each alternatives and discuss which will bring the best benefits, along with the shareholders of the process, is essential. Together with an agreement of the future layout, a plan of actions is also required. The implementation phase and the monitoring conditions that indicate whether and when to exercise the design flexibility and adapt the system to new circumstances are necessary to be defined and planned. With the finalization of this actions and hence this step, the *operational analysis* is closed and *strategic implementation* phase begins.

3.1.5.1 Objectives

1. Evaluation of each alternative design;
2. Chose of future layout design;
3. Definition of a plan of action.

3.1.5.2 Tools and Techniques

- Checklist;
- Gantt chart.

3.1.6 Execute

With the *strategic implementation* phase initiated, the methodology continue with the implementation of the plan of action developed in the previous step. In this step is recommended a close monitoring of the actual results that are being achieved and their comparison with the expected results.

3.1.6.1 Objectives

1. Implementation of plan of action;
2. Monitor outcome.

3.1.6.2 Tools and Techniques

- Work Breakdown Structure;
- Gantt Charts.

3.1.7 Adjust

The methodology closes with a step destined for adjusting actions and developing possible interventions. Additional interventions for maximizing the operational efficiency of equipment and auxiliary formation and skills training of workers are examples of possible adjustments to be made. The main objectives of this step are to target interventions when needed. However, it would be counterproductive to propose and decide upon extreme alternative design changes without using a proper prior *strategic analysis* and *operational analysis* so when it is showed that the execution step is not having the excepted results a new iteration of the methodology needs to be triggered.

With the conclusions taken and this step finished, a complete iteration of the proposed methodology is achieved.

3.1.7.1 Objectives

1. Corrections of deviations of outcomes.

3.1.7.2 Tools and Techniques

- Total Productive Maintenance (TPM);
- Single-Minute Exchange of Dies (SMED);
- Action Plans.

3.2 Data input

In order to execute a complete iteration of this methodology, data collection concerning three aspects of the manufacturing system is required:

Product mix information Information of product structure breakdown, routes and requirements for the future mix. Normally it should be used production requirements of the future period in question;

Layout Information Information of current plant layout, buffers, machines and flow-paths and current characteristics;

Machine Information Dimensions, NPC, Performance; set-up times;

Buffers Information Capacity;

Flow-paths Information Dimensions and speed of transportation;

Historic data of production Information about production and machines utilization regarding past records.

The presented data inputs regards a generic view of product oriented manufacturing system. Depending on the field of application the data input necessary may vary accordingly.

3.3 Continuous monitoring

As a cyclic approach to design a manufacturing system, this methodology requests a continuous monitoring of the conditions that may activate a new iteration of the developed approach. Define and plan the circumstances that determine whether and when to exercise modifications in the layout, triggering a new iteration of this methodology, will support and sustain a stable outcome. Enabling change and adaptability of the system to new circumstances as they come along, in a controlled manner, is a core philosophy of this methodology and for this reason the implementation of any design will require this arrangements.

In each iteration, the manufacturing system reality will present changes. Whether it is a new product or range needed to be introduced in production, whether its consistent demand growth, or whether a previous iteration revealed new events and, triggered the cycle, studying which modifications need to be introduced in the system to achieve high continuous efficiency is reinforced in this methodology. The activation of a new iteration will vary accordingly to the triggers chosen, nevertheless, they will be related to *change*.

3.4 Assessment and limitations

The proposed methodology attempts at shifting the way designing processes are currently being achieved. By distributing over time the decisions of the layout design, and enabling modification of the system in a controlled way, it is embraced the reality of todays industries. As a result a sustained control of variability is attained. Targeting a specific niche of event in this methodology is no longer a setback because when confronted to a changing paradigm or unexpected set of scenarios, an iteration of the methodology will be triggered and the layout design will be corrected, if needed. Thereby a simple and easy approach for controlling the consequences of demand variability in the design process of a manufacturing system is achieved.

With this methodology, by allowing and supporting the modulation of different possible solutions and assessing the consequent results, a greater understanding of the system is achieved and for this reason companies can even discern the best products and components for their facilities and invest in product design and marketing campaigns that influence and induce that decision to customers.

Globally, the methodology is a straightforward approach to resolve new and recurring issues in any industry, concerning the consequences of demand variability. By resorting to an iterative approach a commitment to continuous improvement, in efficiency and productivity, is established. And as defined conceptually, the potential to be used widespread as a problem-solving and process-improvement solution is also captured.

Regarding the limitations of the present methodology, the constrain of time is a critical obstacle. In some cases the approach can be too time consuming for the time frame available to take decisions, whether it is caused by modeling too much information or whether the timing of the arrival of informations of demand changes was to abrupt to complete the iteration. Therefore, if not carefully used, this methodology can present much slower results than a straightforward implementation. Dealing with fast, urgent problems or emergencies is not properly resolved by this methodology. A second limitation is related to the necessary requirements of specialized skills to model and simulate a manufacturing system. Lastly, limitation regarding the extreme necessity of continuous control and the consequences of the lack of monitoring can also be felt.

3.5 Validation method

In order to evaluate and validate the efficiency and effectiveness of this new methodology that is expected to control the consequences of demand variability in the design process of a manufacturing system two distinct validations are applied.

1. **Theoretical validation** Initially a theoretical validation is primarily developed in order to assess and comprehend the limitation of this methodology. This analysis is presented in section 3.4 of the current chapter.

2. **Empirical validation** An empirical validation is then followed and the methodology is tested in a real case study in order to assess if the presented approach captures the complexities of real-life situations and achieves the desired goal. This validation is presented in the next chapters, in chapter 4 the respective case study is presented, in chapter 5 is applied the methodology to the case study and in chapter 6 is assessed the achieved results.

Chapter 4

Case study presentation

In this chapter it will be presented the case study. Initially, a brief introduction contextualizes the company, then a thorough review of the company manufacturing system characteristics takes place, followed by a summarized description of the main limitations and opportunities and finishing with a brief reflection of the applicability of the proposed methodology in relation to the company circumstances.

4.1 IKEA Industry Portugal

The company where this dissertation is being undertaken is a chain link of an world leader in the furniture retail. As one of its top five production countries, IKEA Industry Portugal, thrives by maintaining a strong competitive position in the market place and within the company production units [79].

Controlling the entire value chain, from raw material production to delivery of final product, is one of the strategies followed by the global company to gain competitiveness in the furniture market. The holding company, is composed by three distinct core businesses: franchising, range and supply and industry as seen in figure 4.1.

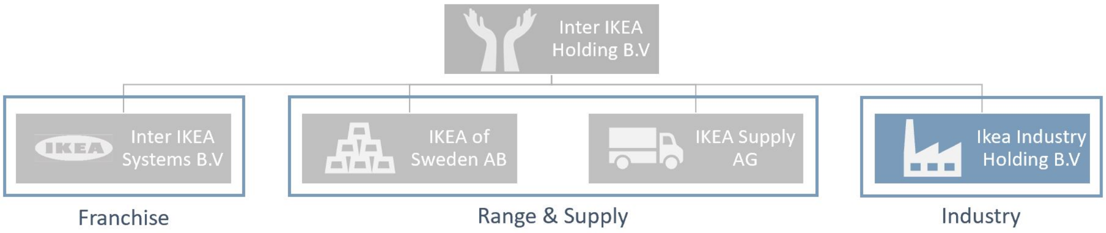


Figure 4.1: Inter IKEA Group constitution (adapted from: [8])

Worldwide the forty production units spread across ten different countries, constitute the largest producer of wooden furniture in the world and constitutes the total production capacity of the global company, in cooperation with external company suppliers [79].

IKEA Industry Portugal will be the company represented in this case study and the only one subjected to analysis.

Located in a strategic point for the exportation of furniture, IKEA Industry Portugal, ensures a percentage of the necessities for three large markets: Europe, Asia Pacific and North America. The sequence of processes involved in production and distribution relative to the company can be characterized, in a simplified way, as illustrated in figure 4.2.

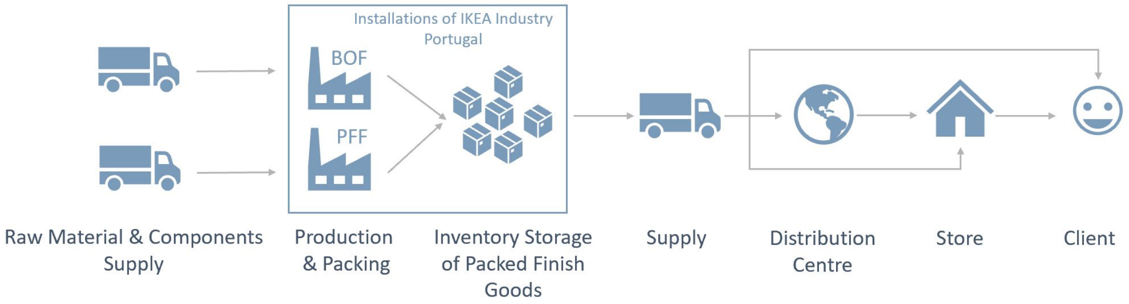


Figure 4.2: IKEA Industry Portugal: supply chain

On site, two distinct factories are installed, Boards On Frame (BOF) and Pigment Furniture Factory (PFF). Characterized by their one independent manufacturing systems, each present distinct ranges of production and exhibit two main flows, distinguished by materials and type of processing employed. PFF factory dedicates its production to kitchen furniture while the BOF factory to bedroom, office and living room furniture. Such reality can be seen of figure 4.3.

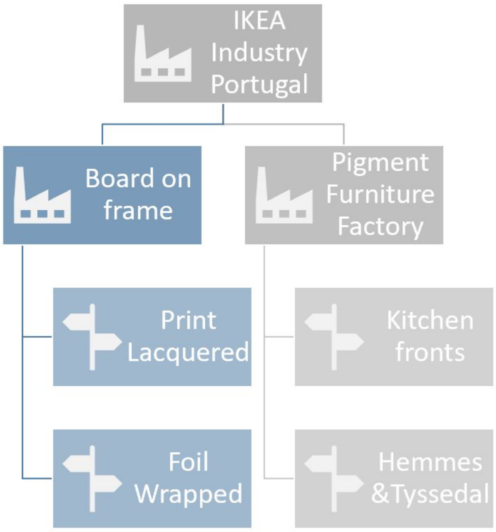


Figure 4.3: IKEA Industry Portugal: factories and main flows

4.2 Challenges and objectives, a design project for the BOF factory

Efficiency and cost-effectiveness are the main drives for IKEA Industry Portugal, in conformity with the cornerstone of the global company business idea: *low prices*. Pursuing such reality, requires a continuous search for new and innovative solutions and the company is committed to this reality. The production unit stated as one of its main objectives to be recognized as a top production supplier for IKEA, and is making efforts to increase its competitiveness, as well as, upgrading its manufacturing system, to which this thesis aims to contribute. It is in this context that a project to re-design the production system of Board On Frame factory was originated.

Influenced by a crescent demand grow and complexity of production processes, the BOF factory intents to attain a new facility that easily accommodates changes in demand, permits growth of the facility and facilitates modifications in production without major stoppages, in the long-term spectrum.

Challenged to developed a layout that will enable growth and change, it is desired a maximum output of production and increased competitiveness of the company over time. Emphasizing volume of production, reduced costs and efficiency are aimed.

Outside of what has already been said in chapter 1 concerning this project, the main objective will be in facilitating change over the manufacturing system life-cycle.

4.3 A brief characterization of the BOF factory

The BOF factory presents a *MTS* production strategy, oriented towards low cost operations and high delivery speed. Accordingly, products are manufactured based on demand forecasts and customer orders are met from stock reserves, typically a four weeks inventory. The MTS method requires thus, an accurate forecast of demand to enable its full benefits. Considered a push-type production, this strategy is employed to manage demand variation, reduce risks, capacitate cost efficient production and simplify the planning process.

The production method in place is characterized as *mass production*. Defined operations and processing times, operative sequence lines, and reduced flexibility are its characteristics. Suitable for stable demand and focus on making quality products at an affordable price. On production, the number of processed products without interruptions, are variable within defined parameters. Lot sizes are employed based on item necessities, physical restrictions, setups and resulting storage space.

The current layout is characterized as a *product layout*, with linear flows and a sequential arrangement of machines that target an efficient production process.

Regarding product specifications, *standard products*, with a seasonal life cycle and stable demands coexist in production.

This section will continue with a brief description regarding product mix characteristics, the present plant layout, the production process and the planning process.

4.3.1 Product mix characteristics

Oriented towards the production of self-assembly furniture, BOF products, feature resistant and light structures. As its primary inputs, raw materials of agglomerate, honeycomb, HDF and borders are used and operated to this effect. Supplied externally are also the remaining manufactured components, which aren't processed in the system but are still required to be packed with the remaining pieces, as it is the case of metal parts and wood screws.

The range of products manufactured exhibits two groups of characteristics, conferred accordingly to the manufacturing process employed, Print-lacquered and Foil-wrapped, mostly attributed to the finishing process.

In F&W, an automated process assembles the structural panels and fills them with a thick honeycomb paper. An application of foil paper around the structure completes the finishing of the Board on Style elements.

In L&P, the panels are assembled depending on shape complexity, in a manual or automated process, using, equally, honeycombs fill. Painting and varnishing are then used to complete the finishing.

Currently, in L&P four different ranges of products are manufactured and in F&W six ranges. Corresponding to 181 distinct final products that are differentiable by width, length, thickness, material, drilling process, finishing and color type.

Over the years product mix have changed and the company points out that in the last two years, greater complexity of volume and variety of ranges are manufactured. Moreover, new products in the next coming years are also foreseen to require new technologies and additional operations to products already existing.

As it is possible to analyze in figures 4.4 and 4.5, this evolution of volume and diversity of ranges, from 2016 to 2018 joining now the forecast of 2019 demonstrates the reality of this changes. The correspondent values are purposely hidden in order to preserve the confidentiality of this informations.

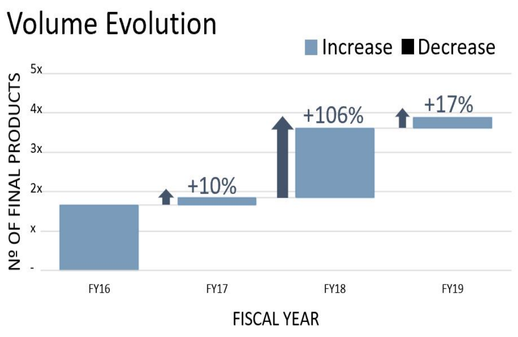


Figure 4.4: Volume evolution

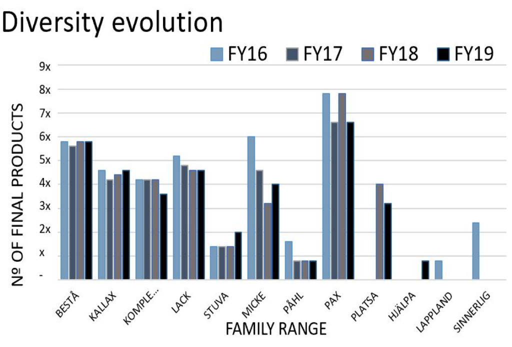


Figure 4.5: Diversity evolution

4.3.2 Plant layout

The production facility is organized as illustrated in figure 4.6, a simplified made-to-scale plant layout that contains information of work centers, buffers and material transportation dimension, shape and location. In this brief presentation of the BOF plant layout, only the production process from cutting to packing will be further described and analyzed as defined within the project scope.

The manufacturing system is constituted by 31 machines, 25 work centers, 13 work-in-process buffers and 3 storages for finish components, *Clouds*. Materials transportation is, predominantly, made by conveyors, with localized used of manual transportation. Configured in dedicated production lines, each area of the facility contains a specific correspondent exit buffer, here marked by numerical digits and correspondent black areas. In total, nine areas of distinct operations can be identified and characterized as exhibited in table 4.1.

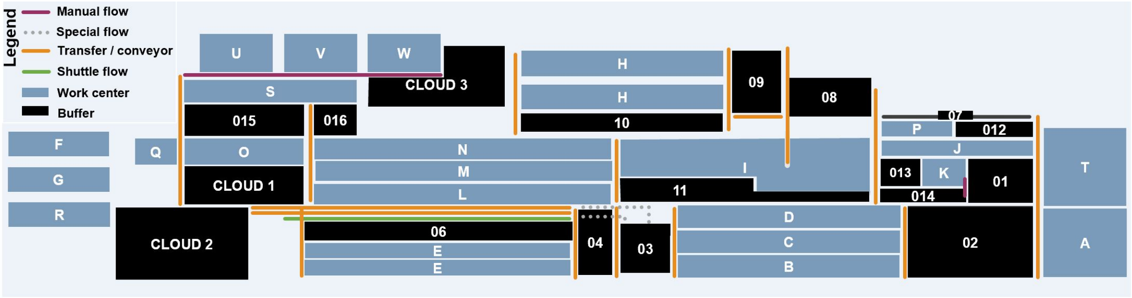


Figure 4.6: Production plant layout

Table 4.1: Work areas of the BOF manufacturing system

Area	Function	Work center
I	Cutting	T Q
II	Frame preparation	P J K
III	Frame assembly	A H
IV	Drilling	B C D N M L S
V	Paint lacquering	E
VI	Foil wrapping	I
VII	Nut insertion	O
VIII	New technology	U V W
IX	Packing	F G R

Since its foundation, in 2006, the facility was only submitted to two interventions regarding structural alterations: increase of *011* buffer size, in 2014; and installation of work centers U and V, in mid 2017, followed by W work center, in late 2017, that came to introduced a new technology. Still, in its early stages, the main flow of components in the area, is made by manual transportation and the volume of processed components is still low, as well as, the utilization of the correspondent machines, to the current moment. As for the rest of work centers and clouds, currently, it is noted a constant overfill and reached of capacity limits. For this reason, within the refereed scope of the project, there are planes to expand the manufacturing system and invest in this new technology.

4.3.3 Production process

Multiple distinct production processes exist that rely on different machines, tools and equipment. Despite their uniqueness and the consequent differences in requirements and features, the production starts invariably in T, by cutting wooden boards into the required shapes. Afterwards, the pieces are forwarded to the required work centers, waiting successively in the respective work-in-process buffers, to be prepared, assembled, drilled, painted or foil wrapped. Each manufactured component is then stored in *cloud*. Finally, the pieces and the remaining necessary components are packed in the F, G or R packing center. The production process can be characterized as illustrated in figure 4.7.

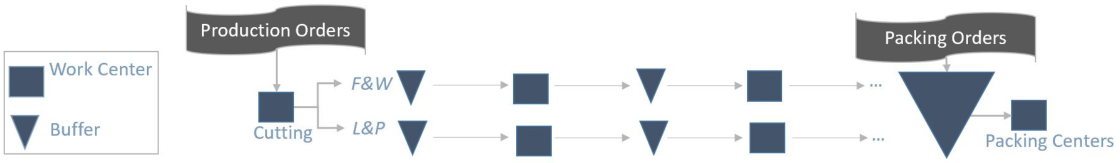


Figure 4.7: Production process

Based on the production mix that was being manufactured in early 2018, all processes are further characterized as illustrated in figure 4.8. It is to be noted that W work center was still not in use in that time, and each work center is located based on flow and not on its location in the factory.

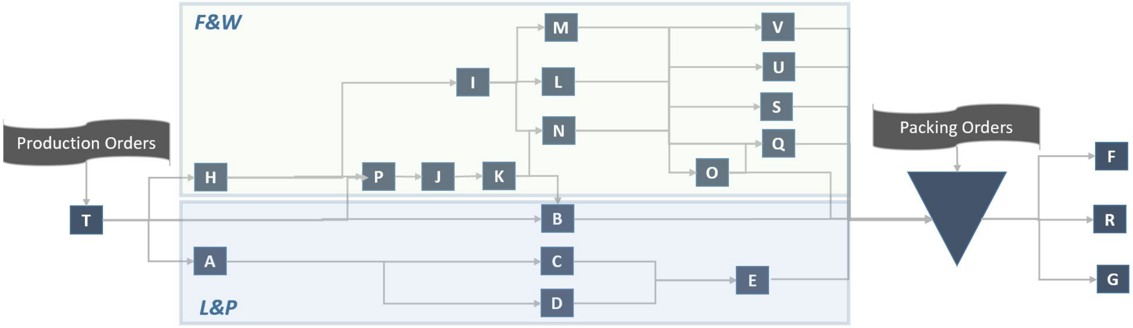


Figure 4.8: Flow diagram of current production mix

Over the years, in the last stages of the manufacturing system, an increase of complexities in the manufacturing processes contributed to an excessive transportation of materials, longer flows and multiple cross ones. This complexity is mostly attributed to an increased introduction of diversity in production that was aggravated recently by the acquisition and integration of the new products and technologies. This changes will only intensify in the coming years, when increased volumes start to be produced and new production flows appear.

4.3.4 Planning process

Long and short term planning are both performed by the organization, considering not only the state of the unit but also including the circumstances of the other global company unit suppliers. By considering multiple planning processes that comprised time horizons from a year to a day duration, the company believes that will achieve a conscious balance of their capacities and inventory levels, securing availability and low total cost.

Annual business plans with a three year period duration are performed for range developments, required volumes and capacities. Equally, budgeting of the coming year on product mix, corresponding volumes and sales prices are performed. Bi-monthly plans are then establish to adjust production volumes of each industry units to the needs of the market, re-allocating IKEA suppliers, adjusting production levels and inventory levels of the category. Followed by monthly plans that will set the definitive production levels and inventory for the site. Weekly adjusts and updates of the master planning are performed based on sales forecast information, publicity campaigns, product discontinuation and launch and production support requirement. Plans for sequencing, releasing and executing the agreed master plan are performed, weekly and daily. The planning process of production is closed a week ahead.

Categorized as 5 stages the planning process executed can be further viewed in figure 4.9.

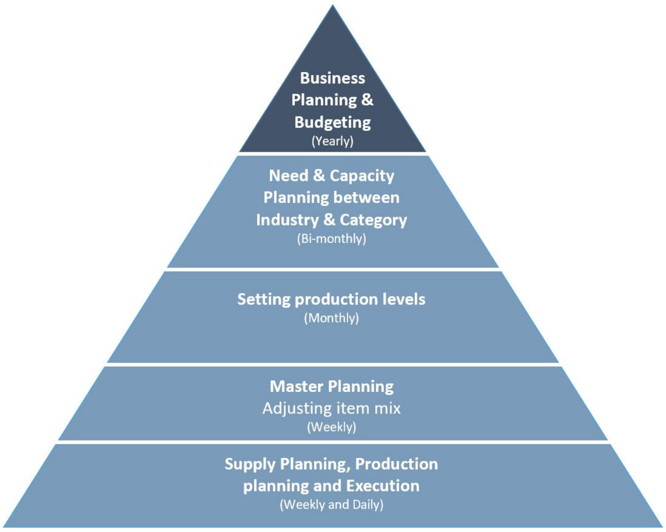


Figure 4.9: The planning levels of the company

Master planning and production planning are developed separately in the facility, in order to ensure a holistic view and balance between fulfillment of customer demand and optimization of production. As the master plan focuses on accurate forecasting demand for the year, production focuses on fulfilling the plan on time, in right quantity and right quality in the most efficient way possible. By considering demand of master plan, scrap percentages, the bottlenecks and critical resources in production, planners define the order releases and their sequence, as well as, the resource allocation, one week in advance by experience. Striving towards efficient flows, demand fulfillment, total output and reliable execution rather than too detailed planning and resource efficiency, the production only creates detailed sequencing plans on single machines for bottlenecks and critical resources. Regarding the frozen period of the master plan it is held as short as possible to create flexibility and to manage demand variability. Eight weeks is thought to be long enough to create supply stability and low total cost nevertheless, currently continuous changes to the plan present a challenge to such period making impossible is fulfillment at the current moment.

Globally the flows of information in the planning processes can be characterized as showed in figure 4.10.

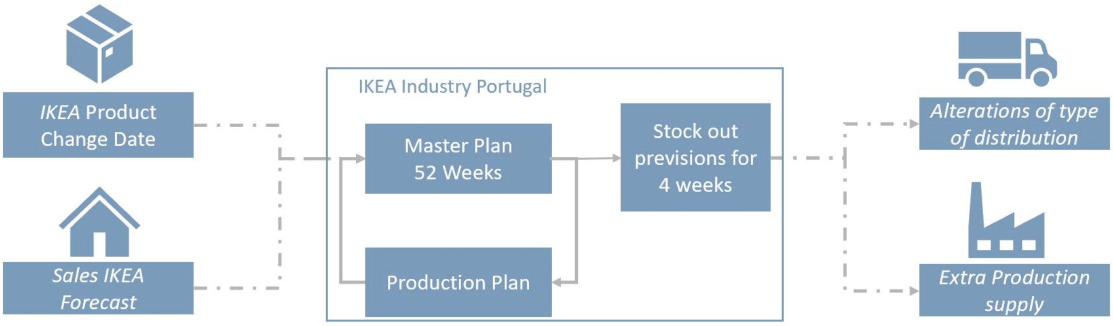


Figure 4.10: Flows of information in planning processes

The occurrence of unexpected events, are common in the facility, leading to frequent rescheduling. Master Planner evaluates when contingency measures need to be taken to guarantee availability of the articles in the market. Using overtime of production and prioritizing orders of production and dispatch for the most critical products are equally used on site.

Due to this occurrences, production goals are not being achieved for some consecutive moths, and it is noted that production is desynchronized with packing, resulting from delays in the components that are necessary to be pack.

4.3.5 Key performance indicators

As inputs for analyzing its performance, IKEA Industry Portugal, uses financial and non-financial indicators. Financial measures are identified as value of production, costs (raw materials and direct labor) and deviations from inventory. Non-financial measures are identified as absenteeism, breakdowns, scrap, rework and overtime.

From this set of measures, the company considers *efficiency* as the main indicator of performance.

$$Efficiency = AvailabilityxPerformance$$

Within the organization, *efficiency* is defined by the product between availability and performance. *Availability* is defined by the quotient between the number of hours of production and the number of hours of production available. In turn, *performance* corresponds to the quotient of the actual production by the expected production volume.

The value of the remaining indicators results from the quotient between actual output and the expected in that period of time.

IKEA evaluates the overall status of the company by analyzing the indicators of each work center.

4.4 Improvements opportunities and adopted approach

The typology of the current production system is dependent of accurate forecasts that influence the planning process, pushing constant updates and corrections to the developed previsions in order to follow the correct demand pattern.

Instability pushes production planners to constantly change schedules, pursuing this changes and reacting to unexpected events such as machine failure or quality problems in production.

If this reality is true in a short term spectrum, in which more flexibility is required in the BOF factory to overcome the consequences of this events, in a long term it stays latent the possible benefits of implementing a *"design for variations* [25]".

Here, the opportunity of improvement does not rely on extinguishing such changes but rather facilitate a reaction and creating the possibility of having alternatives when needed, in order to control and reduce the impact of unexpected changes.

As pointed out by the facility, and as already mentioned, five central conditions are characterizing the manufacturing system at the moment, that will be taken as references in this case study and addressed in further analysis. Production mix changes and future requirements preparations, work centers and clouds necessities for possible growth, flows efficiency in a scenario of increased complexity, production delays control. All to ensure the required flexibility for future adaptations, in growth and change.

Organizations must perform at reliable and successful levels to stay in business. The BOF factory is a clear example that building a new efficient factory based on flexible principles will benefit the company by enabling adjustments in the manufacturing system, over time.

Considering the global picture of the current case study it is possible to conclude that this is a suitable candidate to apply the proposed methodology.

Chapter 5

Methodology implementation

This is the chapter in which the proposed methodology will be applied. The case study, presented in the previous chapter, is the one subjected to analysis. Following the developed procedure, the six-step approach is implemented and a unique iteration of the cycle is executed.

With the objective of re-designing the manufacturing system and controlling the consequences of demand variability, a thoughtful customization of actions was establish.

The followed approach, as well as, the conclusions and decisions made in each step are successively presented in the next sections.

5.1 Strategic analysis

A strategic analysis was initially conducted in order to identify and define a list of possible interventions for the current manufacturing system. The system requirements for the coming year were targeted and the reality of the factory in the long term spectrum was considered.

The uncertainties of the system were characterized and the flexibility dimensions to be integrated were chosen. The set of decisions developed were defined based on current system characteristics, system requirements for the coming year, demand variability pattern and potential trend-breakers.

5.1.1 Observe

By observing the current perspectives of the company on a long term spectrum, a potential trend-breaker may be emerging. Trigger by a new technology, it has the potential of disrupting the production process of all components on site as they are currently being manufactured.

This technology, when applied, confer specific attributes that help the consumer to assembly the piece in a easier and fastest way. On site there is already in production a set of new products with this characteristics. As the new line is having a great consumer response, the company is committed and open to recognize possible future paths in this direction. Thus scenario planning was conducted on the mater to enable the system to transitioning effectively when future incorporations of this technologies are made.

A primary study was conducted with the department of product design to understand the degree of modifications required in each family product of 2019 mix. Currently three types of operations are used by the new technology, each developed in a correspondent work center U, V and W. The objective of this study was to understand firstly which products could be modified and in what way.

The study showed that only 2% of the elements of the production mix of 2019 can not be altered. The other 98% are suitable of being produced with this technology. The results of the conducted study served as inputs to forecast the percentage of components that each work center would have to manufacture, if it was implemented now. The results obtain are showed in table 5.1.

Table 5.1: Previsions of utilization for each technology

Work Center	U	V	U&V	W	Other
Elements of 2019 Mix (%)	32%	30%	25%	11%	2%
L&P flow (%)	67%	68%	100%	24%	100%
F&W flow (%)	33%	32%	0%	76%	0%

The impact and possible use of this technologies were then analyzed in respect to capacity requirements. Based on the capacity of this work centers, that have a maximum output rate of 24 pieces a minute and considering the loading time of production as being a 3 shift day production of seven and a half hours, the minimal number of machines was calculated, and the results are presented in figure 5.1. This analysis was made in order to understand what may be the required space for this technologies in the upcoming years. So that a proper preparation for future expansions can be started and further developed in the future.

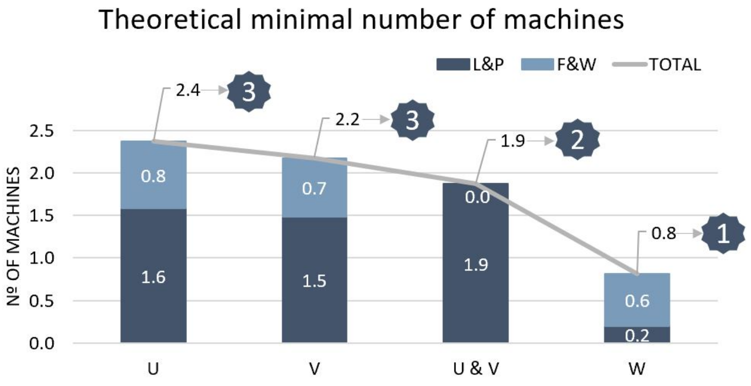


Figure 5.1: Minimal number of machines for each technology

A second study was then developed with the processes department in order to analyze in detailed a case example of a modified product. Product X was chosen for this analysis, as it is the most likely to be firstly introduced. Moreover, it represents the structure and reality of 20% of produced products of the factory, in 2019. The bill of materials and production flows of the same final product were analyses and compared with and with out modifications. In figures 5.2 and 5.3, they are represented respectively.

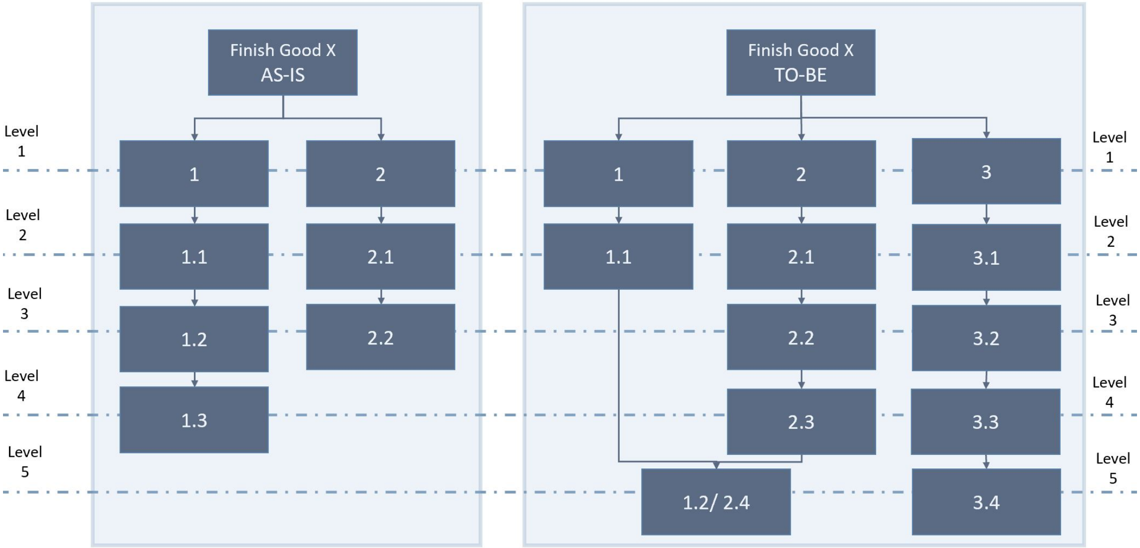


Figure 5.2: Bill of material of finished product X

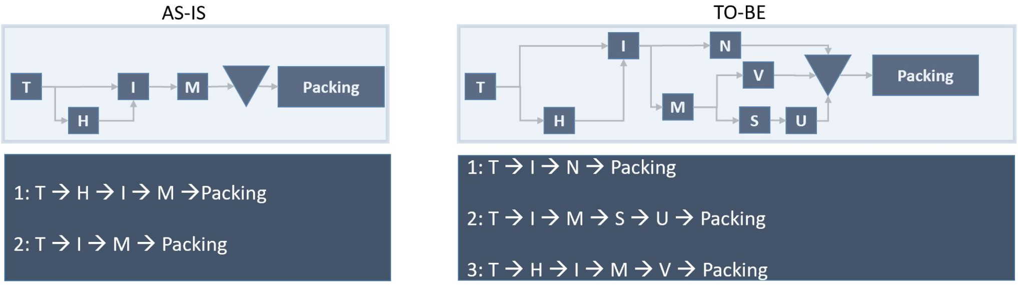


Figure 5.3: Production flow of finished product X

In this case example, the production processes will increase from 7 to 13 operations. Thereby an increased complexity of production flows is certain. Crossed flows will also increase due to the greater number of processes.

This case product will most likely be introduced in production by 2020. Regarding the rest of the families, it is still early to known if they will be adapted or when will they be introduced in production.

For the next year of production, none of the products will be changed and manufactured differently. Despite that, there is a clear opportunity of improvement in analyzing how this technologies should be installed for the future ahead, when the volumes of production become higher. Including preparatives for future expansions and flexibility integrations for the production processes.

It should be mentioned that even though the current products will not be changed, this technologies will still be used and applied to the new ranges of products, as it is the case of HJÄLPA and PLATSA range, that will be produced in the next year.

After analyzing the reality of the manufacturing system in the long term perspective, a short term analysis was employed.

Primarily, an aggregated planning capacity was developed in order to meet the requirements for the forecast demand of the coming year. The effective utilization of each work center was calculated based on current capacities. In this analysis each work center was restricted to a maximum utilization of 85%, in order to count for planned loses as setups or unplanned ones as machine breakdowns.

Moreover, by decreasing the level of utilization not only planned and unplanned loses can be counted for, but also lower levels of WIP can be achieved, one of the most important factors to evaluate in a MTS system. This principle is supported by [80] process improvement principle that states that "increasing utilization will increase WIP, and therefore wait times" [80].

As showed in figure 5.4, work center Q and R are possible critical bottleneck and D, L, C and I may also result in one.

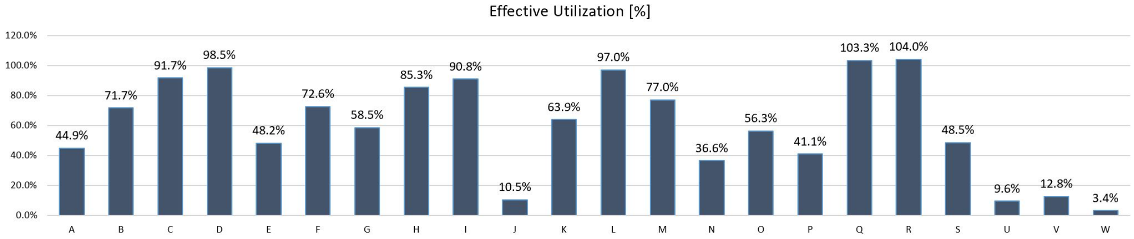


Figure 5.4: Efficiency utilization for the forecast demand of the coming year

After analyzing the system requirements, the future production mix was further studied. Characterized by 180 different finish goods belonging to 10 distinct ranges, this product mix will introduce one new range of production.

Aiming to categorize the products based on their sales value and sales volume and understand which represent a greater or lower strategic importance for the company an ABC analysis was developed, following the Pareto principle. Primarily taking in consideration the product range and then the finish good itself. The analyses are shown in figures 5.5 and 5.6, correspondingly.

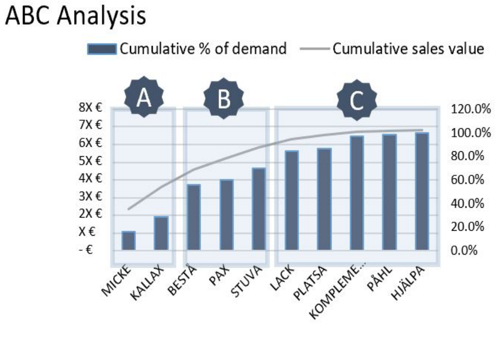


Figure 5.5: 1st ABC analysis: range sales value

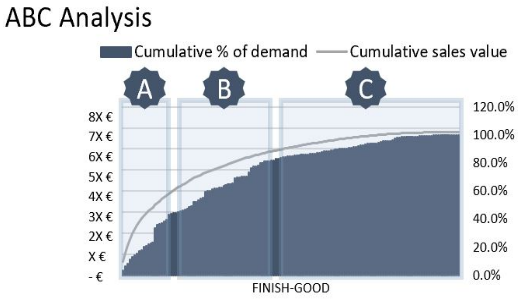


Figure 5.6: 2nd ABC analysis: finish goods sales value

Aiming to categorize the products based on their impact on overall inventory, the necessities of raw material were calculated and a 3rd ABC analysis was made. The different categories of stock to be managed and controlled, in the next year, were analyzed. The ABC resulting graphic is shown in figure 5.7.

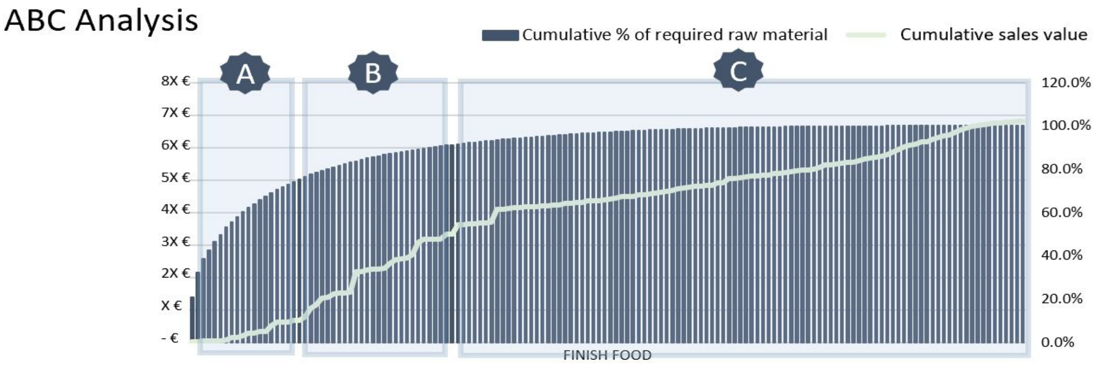


Figure 5.7: 3rd ABC analysis: raw material requirements

It should be mentioned that in each of the three analysis the items classification, as "A", "B" or "C", represent different concepts and required different treatments.

In the first two analysis products "A" represent the 20% of the references that will create the highest sales values and can be used to drive sales growth. In the third analysis product "A' represent the 20% of the references that cause the highest volumes of items in production, and will need to be managed closely with an appropriate order pattern, as 'just-in-time' or lower lot sizes, to avoid excess inventory in production.

To give further insights on this analysis, the values were summarized and are now presented on table 5.2. As for the informations and classifications of each finish good, it was excluded from this document to remain confidential.

Table 5.2: Results of ABC analysis

ABC Analysis	Class	References(%)	Sales Value(%)	Demand(%)
1st	A	20%	52.79%	28.93%
	B	30%	33.24%	40.52%
	C	50%	13.97%	30.55%
2nd	A	20%	65.99%	48.57%
	B	30%	23.12%	36.27%
	C	50%	10.89%	15.16%
ABC Analysis	Class	References(%)	Material requirements(%)	Demand(%)
3rd	A	20%	83.72%	31.93%
	B	30%	13.46%	33.04%
	C	50%	2.82%	35.03%

Taking in consideration that the expected proportions would be 20%-80% for "A" items, 30%-15% for "B" items and 50%-5% for "C" items, with possible variations on the threshold for each class, the results from the 1st and 2nd analysis are clearly more disperse.

Through the results presented in table 5.2 it is possible to say that greater fragmentation of produced sales values is presented. As for the the volumes of raw material produced, they clearly follow the expected results helping a more efficient planning of operations and internal logistics.

Aimed to understand which products and components were produced the fastest, the production mix of 2019 was analyzed. In the long term spectrum it was reasoned that if the factory knew the fastest components and the characteristics that confer this attribute, the product design could not only alter the products to incorporate the new technologies but also include this characteristics to reduce their lead time of production.

In order to achieve this objective the following steps were followed:

1. Identification of the top 30% fastest components in each work center, based on NPC and performance;
2. Identification of the resulting finish goods, that could be packed with the identified components of step 1, taking in consideration the bill of material of each component.
3. Identify the characteristics of the finish goods of step 2 based on: length, width, thickness, carrier, edge, type of drilling and types of glue.

The results were then compared with the total processing times of each components, the number of production processes that required and a risk factor associated with the products, that is the number of slowest operations of that product. With this analysis it was aimed to remove misleading results. 11 elements and 33 components resulted in this analysis, that were analyzed based on their characteristics of production. In this group, 4 ranges of products were represented belonging to 4 different flows of production, 2 from the L&P and 2 from the F&W, as shown in figures 5.8 and 5.9,correspondingly. In order to preserve the confidentiality of the characteristics of production they were excluded from this document.

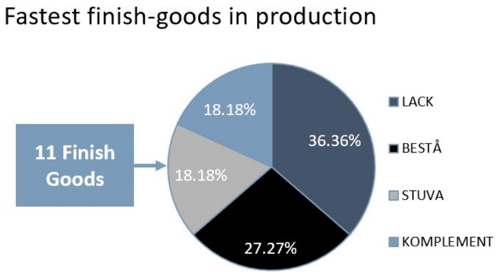


Figure 5.8: Fastest finish-goods in production

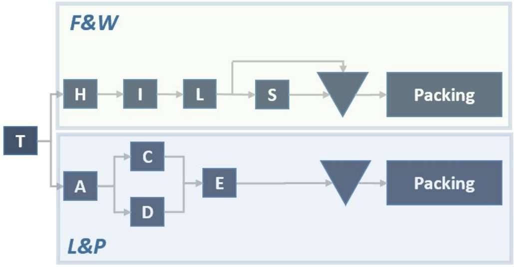


Figure 5.9: Production process of fastest finish-goods

Flow and route of production was also analyzed, resorting to a Sankey diagram. The analysis is shown in figure 5.10. With this tool a greater knowledge and visualization of the flow of materials trough the manufacturing floor and their volumes were able to be characterized. By prioritizing flows with higher volumes and focusing in eliminating cross ones, the opportunities of improvements in the production process can be identified. F&W final processes need to be targeted and the material flow between the two main flows can clearly be shortened by switching work center D with B. It should be mentioned that, for this analysis, the positions of each work center were defined based on their relative positions in the system. Although not made on scale, this analysis still can evidence the crossed flows and thus meet the objectives of this study.

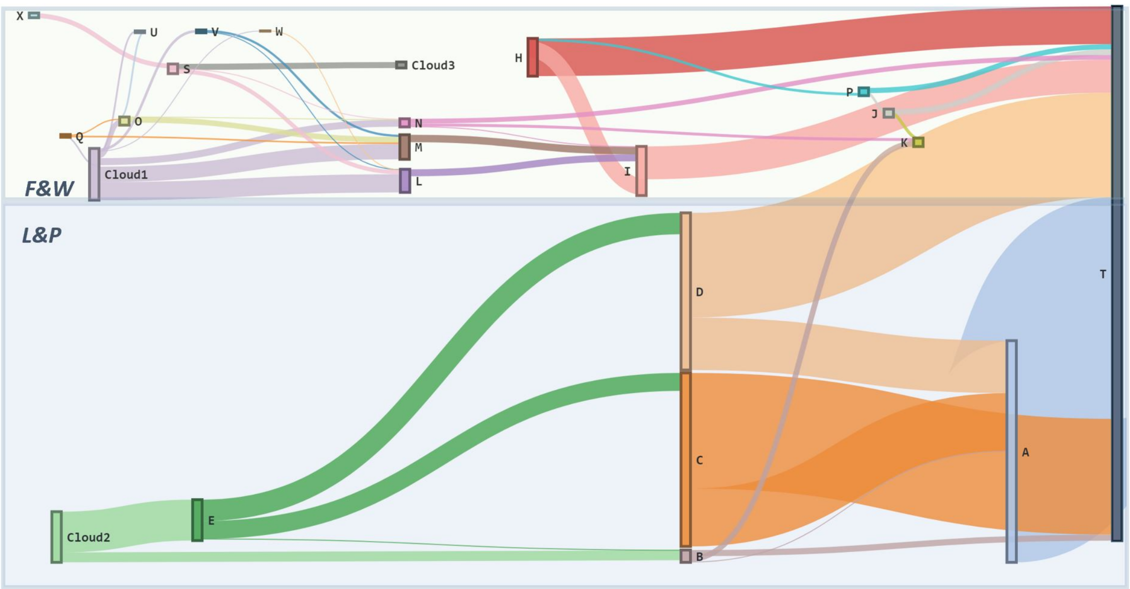


Figure 5.10: Sankey diagram of AS-IS flow of Production

A summarized description of the setbacks of the company was made resorting to an Ishikawa diagram. In figure 5.11 the correspondent diagram is shown. This analysis was developed based on observations of the current manufacturing system, its characteristics, the inputs from the project team, the analysis were presented and the detected limitations of the system.

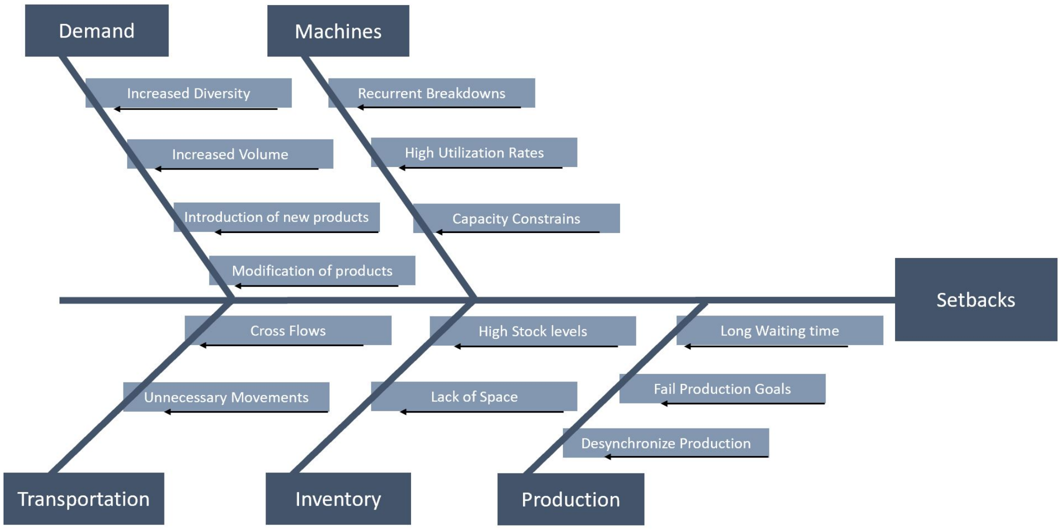


Figure 5.11: Ishikawa diagram of company setbacks

Taking in consideration the setbacks presented on figure 5.11 and the possible uncertainties of a system, presented on table 2.3, chapter 2, it was identified the major uncertainties of the system that will need to be controlled for the future period of production. In table 5.3 it is presented this analysis.

Table 5.3: Major uncertainties of the BOF system

Uncertainty	Environmental uncertainty factors
Internal uncertainties	Machine breakdown
	Queuing delays
	Material shortages
External uncertainties	Changes/fluctuation in the level of demand
	Product mix changes
	Product design changes

5.1.2 Define

In order to control the uncertainties already identified it was analyzed what required flexibility dimensions would need to be integrated in the system. Based on the relationship between environmental uncertainties and manufacturing system dimensions, showed on table 2.4 and the framework of [3], the study was conducted. The resulting choices of this approach are presented on table 5.4.

As the major objectives of the company can be achieved by the application of routing and expansion flexibilities, their introductions were targeted.

Routing flexibility will increase the responsiveness of the system when machines breakdowns occurs, decreasing queuing delays and material shortages in packing. By enabling a easy access for various operations, a more efficient scheduling of parts and a better balance of machine loads can be also achieved.

Expansion flexibility will prepare the manufacturing system to changing environments, as desired. In case of new products introduction, changes on existing products or addition of capacity, implementations time and cost will be reduced.

Following [3] principles in order to achieve such objectives the two component flexibilities, machine and material handling flexibility, need to be applied in the manufacturing system. By installing multipurpose machines with overlapping processes or identical machines in machine

Table 5.4: Flexibility requirements

Uncertainty	Flexibility dimensions	Degree of flexibility
Internal uncertainties	Machine flexibility	Component flexibility
	Material handling flexibility	
	Routing flexibility	System flexibility
External uncertainties	Expansion flexibility	

groups and versatility of material handling system, routing flexibility can be integrated. Furthermore, by having multipurpose machines that do not require special foundation, install infrastructures to support growth, integrate a material handling system that can be more easily routed and facilitate mounting additional shifts, expansion flexibility can be integrated.

With this two flexibilities installed, the system flexibilities chosen will be established. It should be mentioned that the component flexibilities itself will also benefit other aspects of the manufacturing system. Machine flexibility will increase machines utilization and shorter lead times for new products introduction. Material handling flexibility on transportation and buffers, will increase availability of machines and thus utilizations, as well as, reduced throughput times.

The [3] principles of flexibility implementation, [7] alternative layouts and [80] process improvement principles were used as inputs to define possible improvements to the layout. After an reflection and screening of the required set of decisions, by importance and urgency, that would be more beneficial to be modeled and further studied, a group of possible interventions, were defined and are here summarized in table 5.5.

Table 5.5: Possible intervention in the BOF system

Study	Options to model
Assemble study	Option 1: Individual and integrated operations: U, V, U&V
	Option 2: Integrated operations: U&V
	Option 3: Individual operations: U, V
Flexibility dimensions study	Option 1: Material handling flexibility
	Option 2: Machine flexibility
	Option 3: Machine and material handling flexibility

Two groups of distinct simulations were chosen. An assemble study focused on alternative installations of the operations and an flexibility dimensions study focused on possible incorporations of component flexibilities in the layout. Each respective alternative was design and characterized and will be now further presented.

Regarding the assembly study, the differences of each routing logic chosen to be modeled, based on type of components and their required operations, are presented in figure 5.12. Each machine is named after the type of operation that it preforms, corresponding to the respective work center U or/and V. As represented, option 1 uses three different types of machines, option 2 one type and option 3 two types.

Each option of this group of simulations only targets the installation of single machines, excluding the analysis of a possible integrated machine, that can be created by rebuilding the machines of N, M and L work centers to incorporate all operations of U, V, W work centers. Although this analysis was conducted, within the project, it will not be considered within this dissertation. This decision in sustained by the resulting pros and cons of single versus integrated machines. The impact of the two alternatives was analyzed and although a single machine will increase planning decisions, number of workers and transportation, the impact of machine breakdown will be much lower, the number of setups will be reduced and thus increased throughput and reduced work in progress can be achieved, as stated in [80] principles. Also by using single machines, D,C,B and N,M,L work centers can still be sharable resources. Therefore, the integrated installation can be excluded.

As the location of this single machines will be downstream of production and the subsequent operation will be the packing, it was reasoned that this group of simulations would be simplified and only the actual machines would be modeled.

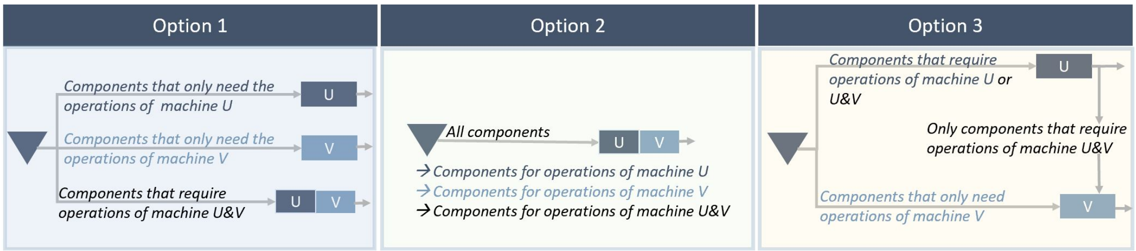


Figure 5.12: Characteristics of the assembly options

Regarding the flexibility dimensions study, a rough-cut layout design was developed for each option, and it can be seen in figures 5.14, 5.15 and 5.16.

Previously to this designs, a conceptual sankey diagram was primarily developed with the objective of understanding what modifications regarding work center locations would benefit uncrossed flow paths. The resulting diagram can be seen in 5.13.

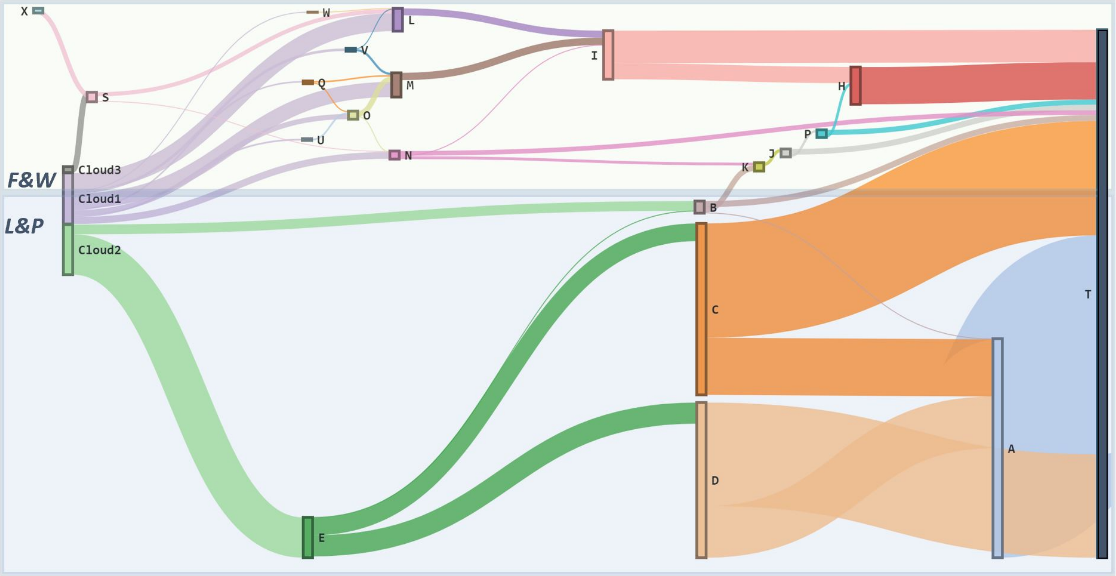


Figure 5.13: Sankey diagram of conceptual flow of production

Focused on conferring to the manufacturing system material handling flexibility on buffers and transportation, option 1 was developed. Two process improvement principles were followed, together with the input of the conceptual flow, that stated that "employing a share buffer with the same total buffer space will improve performance over a system with dedicated buffers" [80] and "increasing buffer sizes will both increase throughput and decrease WIP" [80]. A rough-cut layout was then developed together with a representation of the flow paths and is now presented on figure 5.14.

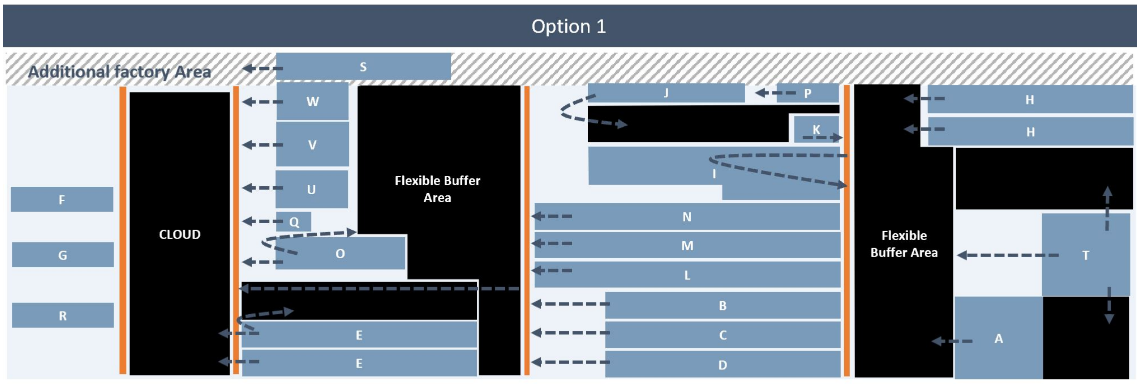


Figure 5.14: Flexibility dimensions study: material handling flexibility integration

Option 2, on the other hand, focused on conferring machine flexibility to the manufacturing system. After analyzing past data of MTBF indexes, work centers B, C, D, N, M, L were target. Each exhibit the same level of MTBF and one the lowest indexes in the manufacturing system. As all work centers belong to the same group of technologies, the creation of a multipurpose group of identical machines that can produce any product in the manufacturing system and redistribute task when needed was chosen. To achieve this goal, only L and B work centers would need to be substituted, as the other work centers (M, N, C, D) already have this characteristics.

The process principles that served as references for this option are based on two principles. One stating that flexible machines "will improve performance", present "significantly less WIP", require fewer machines, will "not prevent processing of any of the entities" when a machine breakdown occurs and will "make it easier to introduce new entities into the system" [80]. Another stating that "split tasks across parallel servers to utilize idle resources" "will increase throughput, reduce WIP, and improve timely delivery" [80].

A rough-cut layout was then developed and is now presented on figure 5.15.

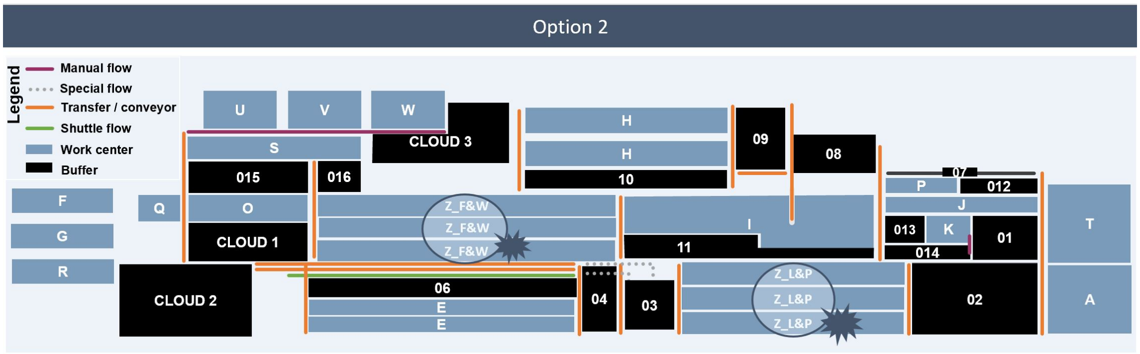


Figure 5.15: Flexibility dimensions study: machine flexibility

Option 3 focus on combining machine and material handling flexibility. In order to enable easy modifications to respond to changes in demand, product mix and tasks, a ladder layout configuration was chosen, giving now more emphasis to the flow path. The decisions chosen on option 1 and 2 remain, this way flexible buffers and group of technology are kept. A rough-cut layout was then developed and is now presented on figure 5.16.

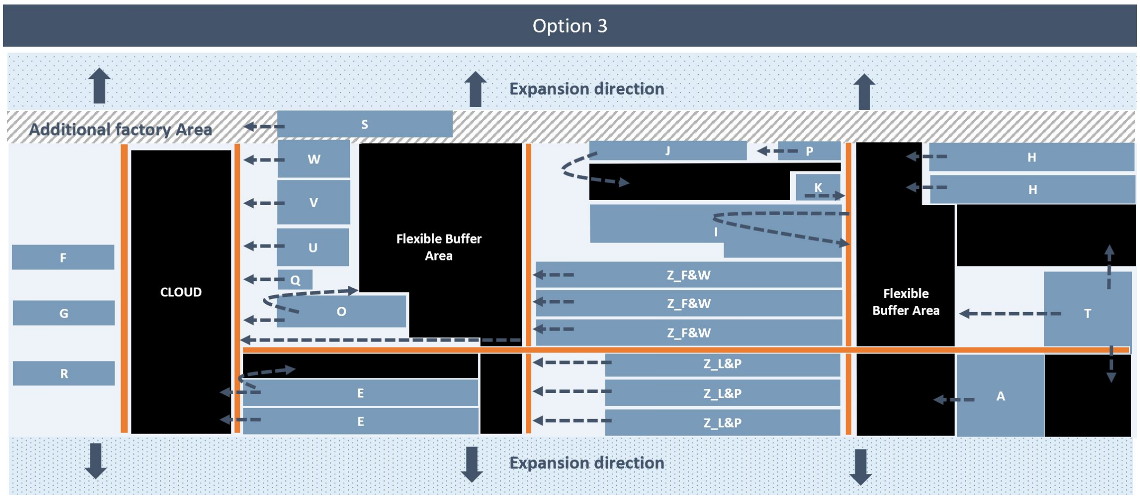


Figure 5.16: Flexibility dimensions study: machine and material handling integration flexibility

5.2 Operational analysis

After concluding the strategic evaluation of the system and having identified and limited possible interventions to the manufacturing system, a operational analysis was developed. Using discrete events simulation, each intervention was modeled and compared with the current manufacturing system simulation. The impact of each alternative was evaluated and the choice of the future manufacturing system was sustained. A plan of action began to be prepared together with the project team, to conduct the required interventions.

5.2.1 Model

In order to model and simulate each possible intervention SIMIO modeling tool was used. With a rapid modeling capability and no requirements of programming, it presented a suitable candidate for this case study.

Two groups of distinct simulations, assembly and flexibility integration, were modeled following distinct approaches and characteristics. On one hand, the assembly study was characterized by simple models that focus just on the three work center in question. On the other hand, the flexibility integration study integrate different versions of the full model of the manufacturing system, from cutting to packing operation. In the next sections the two groups of simulations and each of their alternatives will be further presented.

5.2.1.1 Assembly study

Regarding the assembly study, each option was modulated accordingly to the specifications showed on figure 5.12 and three independent models were created.

As inputs it was used the elements of the 2019 mix that are suitable for being produced with the new technology. Three types of entities were this way defined, representing their required operations and thus their routes, as presented in table 5.6.

Table 5.6: Entities of the assembly models

U	Elements that will need exclusively to be processed in a machine of work center U
V	Elements that will need exclusively to be processed in a machine of work center V
UV	Elements that will need to be processed in in a machine of work center U and also V

As output, machines utilization were analyzed. Moreover, in order to choose the best option for the company, three factors were considered, number of required machines, cost of installation and the resulting machine utilization.

The results can be seen in table 5.7 with exception of the cost of installation that was excluded to preserve its confidentiality.

Table 5.7: Results of the assembly study

Option		U	V	U&V
1st	Number of machines to install	3	3	2
	Machine Utilization	79.05%	72.54%	93.50%
2nd	Number of machines to install	0	0	7
	Machine Utilization	-	-	91.69%
	Tools Utilization	30.30%	28.90%	-
	Aggregated tools utilization			59.20%
3rd	Number of machines to install	5	5	0
	Machine Utilization	84.83%	80.93%	-

Option 1 is the option that requires the lower number of machines however it is not the one that represents the lowest investment. Option 2 represents the highest investment for the company and highest capacity not used. Although the machine itself has a utilization rate of 91.69%, in reality the aggregated tools utilization are only at 59%, being that the most of the time one of the tools is not in use. Option 3 has the higher machine flexibility, lower investment, a machine utilization in the 85% percentage and reduced processing time, demonstrating to be the best one for the company.

5.2.1.2 Flexibility dimensions study

Regarding the flexibility dimensions study, before starting the modeling process of each defined option, the current layout was analyzed. In order to have a reliable term of comparison between current and future layout performances in the next year period, the existing simulation model of the BOF manufacturing system was updated and runned.

The process of data collection was extensive and targeted all inputs refereed and presented in figure A.1. The product mix and volumes correspond to the forecast of 2019 production, as well as, the performances of machines per item and indexes of MTBR, MTBF, as it is expected improvements for the coming year with the interventions of the Lean department. All other inputs were updated accordingly to the current state and characteristics of the manufacturing system dated on march, 2018.

A 12 weeks production plan period was defined as the ideal time to accurately represent the future scenario of the factory while not increasing drastically the processing time of the simulation. A periodic plan that cycles every quarter was targeted.

Following the current rules of the planning department, typical lot sizes and order release frequencies, a production and packing plan was developed by the project team in order to produce and pack all types of finish goods in the 12 week period. The sequence of production was defined in order to restrict a 500 minutes period for each flow of production, at a time and guaranty a balanced production. The resulting plan served as input to all simulations developed.

A two weeks warm up period was defined in each simulation, in order to gather a reliable set of informations that will represent the reality of the factory when in production.

In order to further analyzed the models 5 KPI were chosen: Production, packing, average buffer size, total blocked time and total setup time. All indicators are programmed and available in the simulator.

In agreement with all above information the updated model was runned. The simulation of the current layout revealed that the expected average output value packed for the coming year, is bellow demand by 3%. As showed in figure 5.17, the output variability compromised the plan adherence that resulted in a decreased output overall.

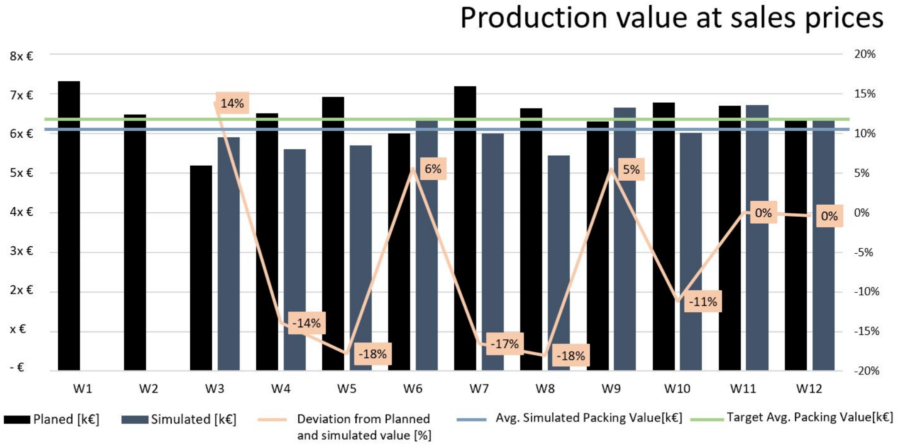


Figure 5.17: Production output value at sales prices of current layout for coming year

By analyzing in more detailed the processed entities, the buffer state and work centers it was concluded that L&P flow has the available capacity for 2019 production forecast however F&W was not. The results also show that resizing buffers 09 and 10 are required to eliminate blocked times of the F&W flow, in particular work centers H, I and N. Maintenance improvements are also recommended in order to reduce hight values of failure times and free additional capacity, being that Q work center is the most critical one. Each work center was analyzed in detailed regarding average percentage of processing time, waiting time, failure time, blocked time and setup time. All information were summarized and are now presented in figure 5.18.

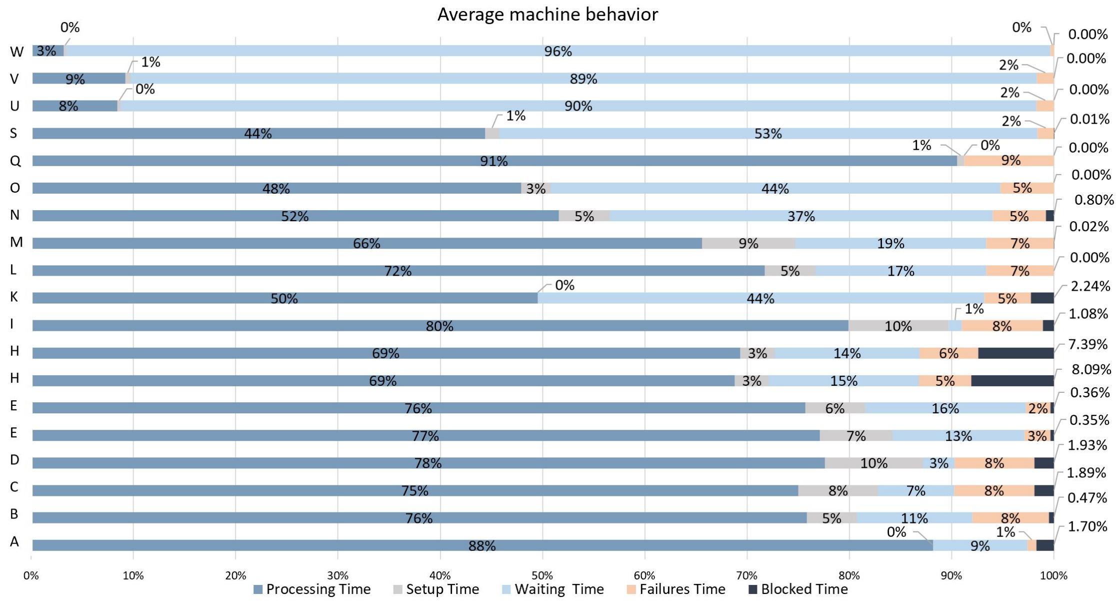


Figure 5.18: Average work center behavior for the current layout for coming year

In order to decrease the output variability and guaranty a better adherence to the plan, in the current circumstances and if no other layout alterations were implemented, it is required to resize buffers, develop maintenance improvements to improve failure stoppages and decrease the setup times performed. This interventions are critical to achieve the levels of production forecasted for 2019.

To support this conclusions a second run of the updated model was developed, without considering failures of machines. By analyzing the output components, it was showed that the output variability reduces from +/-13% to +/- 8%. In figure 5.19 the results can be compared.

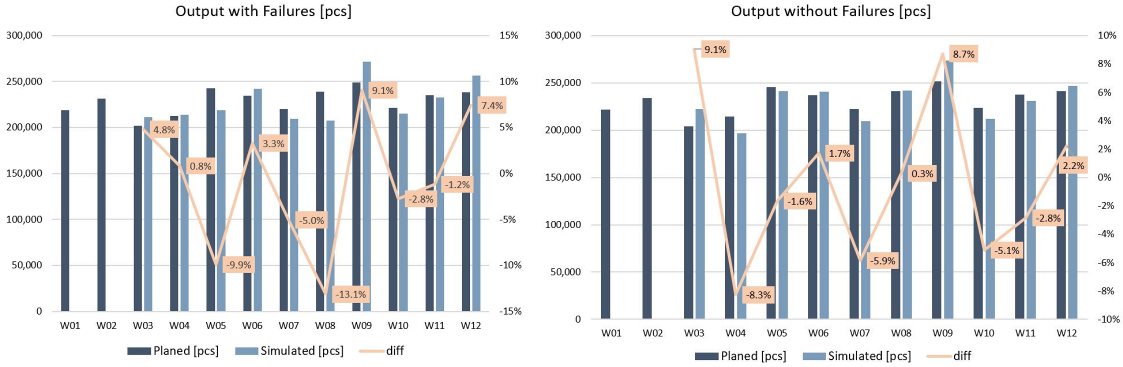


Figure 5.19: Plan adherence analysis

A sensitivity analysis was also developed to understand how different failures affect the packing output. Seven simulations were runned with different seeds. The results were then compared with the scenario that do not considered any failures. In figure 5.20 it is possible to observe the different values achieved.

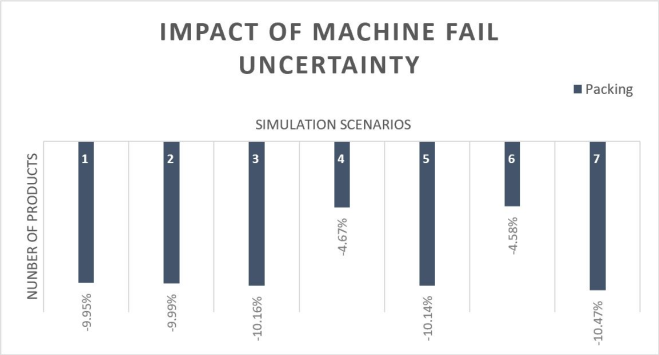


Figure 5.20: Sensitivity analysis of failures

In order to understand the degree of alterations on buffers sizes, also another simulation was developed. Buffers 9 and 10 were dimensioned and result are now presented on table 5.8.

Table 5.8: Buffer dimensioning results

Buffer	Actual size (m)	Requirements(m)	Increase(%)
9	527	800	52%
10	682.5	1000	47%

After analyzing the current layout the defined three options would had been modulated and analyzed following the same tools and characteristics used by the current simulation model presented on appendix A.

5.2.2 Discuss

After simulating and modeling all required alternatives, a step of thoughtfully deliberation would follow and the future layout design chosen. A final decision would then be made by the company and a correspondent plan of action would be elaborated.

As refereed on section 1.3, within the objectives of this dissertation, it was not expected to develop further analysis for the company. Therefore this part of the approach was excluded from analysis. Notwithstanding with the data analyzed so far preliminary conclusions and recommendations were developed.

5.2.2.1 Assembly study

Regarding the assembly study, option 3 should be chosen and thus individual machines, with work centers U and V are recommended to be installed. As currently the manufacturing system has already this configuration no further plan of actions is required to be defined in the long term.

Nevertheless it should be mentioned that space requirements of this work center needs to be a concern and the area around them must be cleared, as a increase of until 4 machines in the future years may be required. When the volumes of this work center rises, a cycle of the proposed methodology will need to be triggered.

5.2.2.2 Flexibility dimensions study

Regarding the flexibility dimensions study, based on the data analyzed regarding the current layout a preliminary plan of action is recommend to be developed, by the lean and process departments, to reduce setup times and failures of machines. Work centers D,C,E,I,M should be prioritized regarding setup times and work centers B,C,D,H,I,L,M,N,O,Q regarding machine failures.

5.3 Strategic implementation

An strategic implementation would follow to support a efficient execution of the necessary interventions in the layout.

The developed plan of action would be executed and a close monitoring of the actual results would be made. Analyzing the necessity of further interventions as additional procedures to maximize the operational efficiency of equipment or auxiliary formation and skills training of workers would also be developed.

At this stage, a complete cycle of the proposed methodology would have been achieved. Since, within the objectives of this dissertation, it was not expected to be developed further analysis for the company on such matter, this part of the methodology was excluded from further analysis.

Chapter 6

Conclusions and future work

This closing chapter begins by enumerating the main takeaways from this dissertation. A reflection on the importance of flexibility integration in the design process of a manufacturing system is developed and some suggestions regarding future work are presented.

6.1 Implications for practice

A key takeaway from this work is that flexibility is a crucial aspect to incorporate when designing a manufacturing system. Both theoretical and practical grounds lead us to recognize that implementing suitable flexibility dimensions in manufacturing systems is the future. No global solution will perform at its best in all cases and each company will need to actively analyze the best dimensions for their reality.

Implementing a design procedure that distributes over time the decisions of layout design, enabling modification of the system in a controlled way can be a suitable solution for the new application procedure for flexibility and the perfect methodology to control demand variability in the design of manufacturing systems. By removing the necessity for long term forecasts, error deviations are no longer critical and precise prediction values are acceptable, as well as, targeting a specific niche of event. When confronted to a changing paradigm or unexpected set of scenarios, the layout design will be corrected, if needed.

The key to the success of this procedure relies on the choice of the flexibility dimensions and the understanding of the uncertainties of the manufacturing system in question. As constant interventions will destabilize the system and cause more harm than good, choosing the right kind of flexibility, that will enable the system to cope with the uncertainties and variability delaying the necessity for interventions, is crucial.

The disadvantage of this process relies on its intensive tailor analysis induced by the necessity of constant monitoring the system. As this analysis referees to the global manufacturing system, the process can be extremely slow for data collection and analysis.

This characteristic can be overcome by the creation and support of an appropriated organizational structure that is in charge of all related business of such matters.

6.2 Future work

Flexibility in design opens the door to new opportunities. The procedures for creating effective flexibility in design are still not well establish [25], however, it is believed that this dissertation is a step in the right direction. Flexibility is only beginning to be truly explored and there are not so many companies routinely creating flexible designs [25].

The proposed methodology, although it could not be extensively tested in the case study, demonstrates great promise. Further studies are now required to reasonably evaluate this methodology as a valid approach for flexibility integration and for controlling demand variability.

Regarding the case study, the *flexibility dimensions study* is required to be concluded and a follow-up to evaluate the implemented results in the actual production system is recommended. Moreover, a study to analyze the impact of required design alterations caused by fluctuations in the product mix would also reinforce a better evaluation of the results of this methodology.

Regarding the methodology itself, the application of this procedure to other case studies is required. Moreover, accessing their results in comparison with other procedures as Neufville and Scholtes methods would be greatly beneficial.

This methodology could also improve its results by integrating other procedures from data analysis methods to different flexibility dimensions frameworks. Since this methodology was developed without restrictions on such matter, enabling the user to choose the ones they prefer, this matter is a open subject to be incorporated.

Appendix A

BOF factory simulator model

BOF simulator model represents a made to scale plant of BOF factory, that accurately simulates operations from cutting to packing. Developed in SIMIO software by INESC TEC, it was programmed to interact with three other tools:

ETL tool that automatically load and transform data from IKEA to the Simulation Model;

Automated Planning Tool that automatically generates an production plan, portion batch sizes and sequence production according to the order release rules;

Dashboard that analyzes the resulting output of Simulation, Buffer evolution, value generated.

The integration of this tools in the system and the flow of information can be seen in the system schematic of figure A.1.

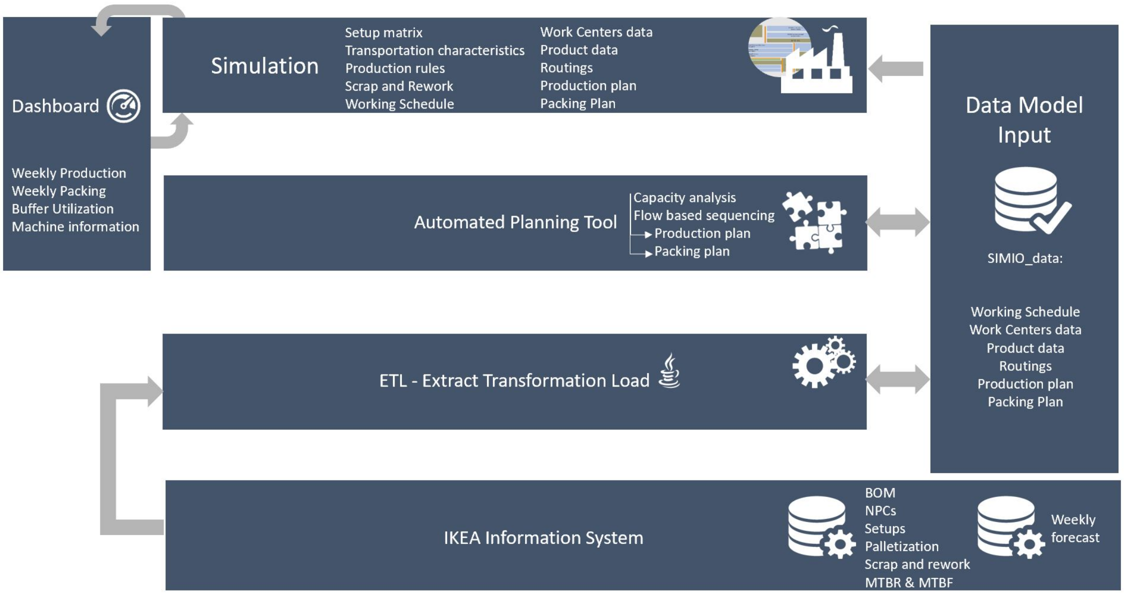


Figure A.1: System schematic (adapted from: INESC TEC)

As inputs this model it is used detailed characteristics of the production line as routings, bill of materials, setup up matrix's, working schedules, production and packing plans, sequencing rules, machines, buffers and cars data. As outputs, informations resulting production and packing, as well as, buffer and machine information of utilization over the simulated period is available.

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