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A MILP for multi-machine injection moulding sequencing in the scope of C2NET Project

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Abstract: The goal of C2NET European H2020 Funded Project is the creation of cloud-enabled tools for supporting the SMEs supply network optimization of manufacturing and logistic assets based on collaborative demand, production and delivery plans. In the scope of C2NET Project, and particularly in the Optimisation module (C2NET OPT), this paper proposes a novel holistic mixed integer linear programing (MILP) model to optimise the injection sequencing in a multi-machine case. The results of the MILP will support the production planner decision-making process in the calculation of (i) moulds setup in certain machines, and (ii) the amount of products to produce in order to minimise the setup, inventory, and backorders costs. The designed MILP takes part of the algorithms repository created in C2NET European Funded Project to solve realistic industry planning problems. The MILP is verified in realistic data considering three data sets with different sizes, in order to test its the computation efficiency.

Key words: MILP, Sequencing, Injection, Moulds, Multi-Machine, Automotive.

1. Introduction

The current situation in the European industrial park highlights the restricted access to advanced management systems and collaborative tools for small and medium sized enterprises (SMEs), being this tools limited to large enterprises due to the high levels of costs and complexity associated (European Commission, 2013). Nevertheless, the importance of having a applying this tools within the SMEs is considered a key factor, since the utilisation of advanced management tools systems and services will enhance enterprises competitiveness by increasing their agility and adaptability to deal with rapid evolutions of existing and future markets (European Commission, 2008).

SMEs manufacturing value chains are distributed and dependent on complex information and material flows requiring new approaches to reduce the complexity of manufacturing management systems. They need ubiquitous tools supporting collaboration among value chain partners and providing advanced algorithms to achieve holistic global and local optimization of manufacturing assets and to respond faster and more efficiently to unforeseen changes. C2NET aims to collect the most promising results from R&D EU Framework Program projects and build a novel Cloud Architecture to provide SMEs affordable tools (in term of cost and usability) to help them to overcome the current economic crisis and to enhance their competitiveness in the global economy. In general, C2NET (Cloud Collaborative Manufacturing Networks) European Project aims at

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the creation of cloud-enabled tools for supporting SMEs supply network in the optimisation of their manufacturing and logistic planning (Andres *et al.,* 2016c) based on the jointly planning, coordination and integration of processes, participating all network entities. Due to the current characteristics of uncertainty in the markets and economic crisis, there is a need to encourage collaboration tools to reduce costs and increase trust and accountability to market requirements. This study presents an overview of the research carried out in the H2020 European Project: Cloud Collaborative Manufacturing Networks (C2NET.

1.1. C2NET Objectives

Specifically, the goal of C2NET Project is the creation of cloud-enabled tools for supporting the SMEs supply network optimization of manufacturing and logistic assets based on collaborative demand, production and delivery plans. C2NET Project will provide a scalable real-time architecture, platform and software to allow the supply network partners:

- to master complexity and data security of the supply network,
- to store and share product, process and logistic data,
- to optimize the manufacturing assets by the collaborative computation of production plans,
- to optimize the logistics assets through efficient replenishment, manufacturing and delivery plans and
- to render the complete set of supply chain management information on the any digital mobile device (PC, tablets, smartphones) of decision makers enabling them to monitor, visualize, control, share and collaborate.

The specific technical and functional objectives of the project are described next:

- Implementation of C2NET Data Collection Framework (C2NET DCF) for IoT-based continuous data collection from supply network resources.
- Implementation of C2NET Optimizer (C2NET OPT) for the optimization of manufacturing and logistics assets of the supply network by the collaborative computation of production, replenishment and delivery plans.
- Implementation of C2NET Collaboration Tools (C2NET COT) for providing support to the collaborative processes of the supply network.
- Implementation of C2NET Cloud Platform (C2NET CPL) to integrate the data module, the optimizers and the collaborative tools in the cloud.
- To provide new ways to securely store relevant information from supply network partners in public cloud, community cloud or private cloud, ensuring data security and provide the ability of data sharing and data analytics.
- To provide new tools for supporting the supply network optimization of manufacturing and logistic assets.
- To provide new tools to support decision-makers in collaborative processes with intuitive UIs that display in real-time the right data at the right time, built in advanced apps for mobile devices for selective management functionalities across the supply network.
- To provide a new cloud space for allowing the access to all the participants in the value chain to support their decisions and processes enhancement.

2. C2NET Results and Impacts

Globalisation and new types of innovation processes have over the last few decades reshaped in new ways the organisation of value chains. SMEs have an incentive to identify emerging activities that will give them a new competitive advantage. Cooperation within a network may be a sensible strategy for preventing the decay of their traditional specialisation (Commission, 2012). Networks of firms are structures specifically created for active collaboration (Camarinha-Matos and Afsarmanesh, 2005). This collaboration could be open-ended or focused on a specific project task. They may or may not be confined to a specific geographical location and set of industries (Camarinha-Matos and Afsarmanesh, 2008). Enterprises belonging to a network make autonomous decisions, according to what is in their best interest, being sometimes difficult to be inside the network when contradictions among enterprises appear (Andres and Poler, 2016).

In the global economy, there is a growing interest in new organisational structures, which are flexible enough to respond to market changes and at the same time solid enough, with strategies and objectives aligned, to take on cooperative projects. Networks have been identified as crucial instruments for implementing the EU's Europe 2020 strategy.

C2NET fulfils the European industry needs providing advanced methods and tools to address economic and risk assessments in order to support complex decision-making as the management of co-evolution of products-services and the related production systems, the evaluation of alternative configurations of the network of actors involved in the global supply chain, or integration of new technologies in the factory.

In the light of this, C2NET Architecture is proposed with the aim of providing affordable tools to SMEs in order to deal with complex management systems and establish stable and sustainable collaborative processes within the enterprises of the network.

2.1. C2NET Architecture

C2NET Architecture is composed by the Cloud Platform (C2NET CPL), the Data Collection Framework (C2NET DCF), the Optimizer (C2NET OPT) and the Collaboration Tools (C2NET COT) (Figure 1).

The C2NET CPL will provide cloud access to information collected from heterogeneous and distributed sources to create global and local production plans to optimize the processes using the data received from customers, suppliers and manufacturers. This will result on faster and more efficient decision making which have to be made

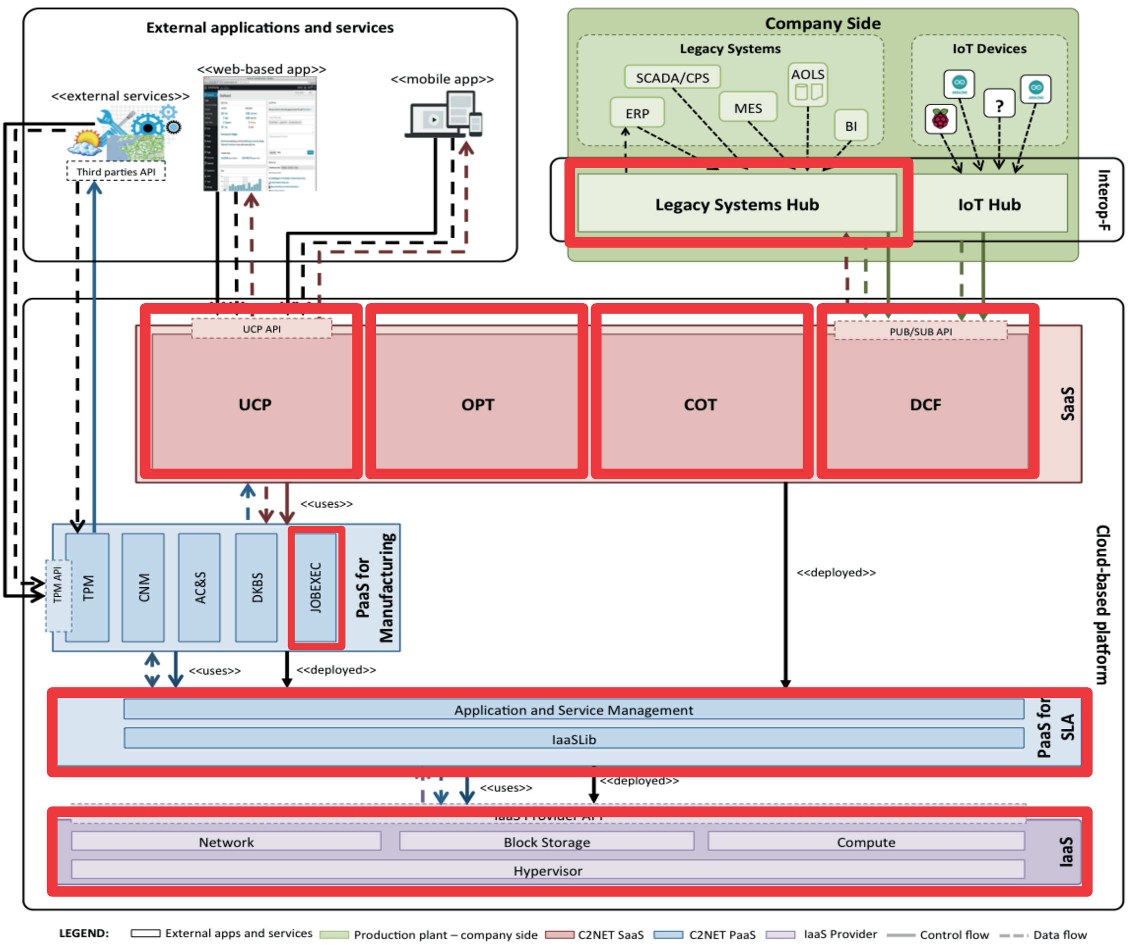

Figure 1. C2NET Architecture (Lauras *et al.,* 2015) (Andres *et al.,* 2016c).

due to market changes, high competition and customization requirements. C2NET CPL will allow collaborative production as production, distribution, supply and customers plans will be calculated based on real time information coming from real-world resources and considering all the actors involved in the process. As information will be available in the cloud, C2NET CPL will enable the possibility to provide relevant information to different personnel using mobile devices when and where is needed, to increase the capability for better and faster decision making when changes in production need to be done.

The C2NET DCF will enable real time information collection from the different value chain enterprise systems and/or physical devices, thus providing the C2NET platform with a holistic view on the network. This will stimulate a fast knowledge feedback loop, which will enable companies to become more effective and react faster to market changes.

The C2NET OPT will provide advanced optimization algorithms for the collaborative computation of production, replenishment and delivery plans with the aim of optimize the use of manufacturing and logistics assets of the supply network from a holistic point of view.

The C2NET COT will propose a concrete solution to support the collaborative value chain by facilitating the diagnosis of any source of divergence of the collaboration with regard to expected situation. Moreover the C2NET COT will be able to support the adaptation of the stakeholders' behaviours by implementing reaction mechanisms based on global and local optimization algorithms.

For more information about each C2NET module we refer readers to (Andres *et al.,* 2016c)

3. C2NET Industry Validation

C2NET project is directly connected with the Industrial application perspective. It is designed to comprehensively cover real entire supply chains considering all stages of manufacturing, distribution and sales to supply a product to market.

C2NET project has the purpose to connect the Industrial, the Research and the Development perspectives. To this end four industrial Pilots are considered in the project, belonging to different industrial sectors, including the automotive, dermo-cosmetics, metalworking SMEs and OEM production of hydraulic and lubrication systems. The Automotive Pilot centers its attention in the collaborative production planning and synchronized replenishment of car components. The Dermo Cosmetics Pilot focuses on collaboration for an agile production and distribution of dermo-cosmetics. The Metalworking SME's network deals with sheet metal supply chain to metalworking industry. Finally, the OEM focuses on the sub supplier value stream collaboration for product on time delivery (OTD) for customers.

The validation of the C2NET Cloud Services in the industry will not only serve for the verification of the C2NET Architecture but also for validation of the integrated modules when implemented in real networks of enterprises. The implementation C2NET Cloud Services will provide developers the required feedback for the platform improvement. Sharing the experiences and best practices will contribute to the adjustment and refinement of C2NET, and will contribute to the identification of avenues of exploitation, and strengths and weaknesses of the cloud platform according to the expectations and needs of the intended final users.

This paper is going to focus in the Automotive Pilot, to study the needs that the enterprises belonging to this pilot have in their production plans, and how the literature plans cover the potential integration of collaborative replenishment, production and delivery plans.

4. The Automotive Pilot

The automotive pilot is framed in the automotive industrial sector and deals with collaborative production planning and synchronised replenishment of car components. The studied pilot consists of the first and second-tiers fully dedicated to the car assembly.

The automotive industrial pilot comprises two manufacturing companies of the Automotive Supply Chain. One is a First Tier and the other its supplier, a Second Tier (Figure 2).

The first and second-tier supplier will use the C2NET cloud infrastructure, platform and software to optimally calculate both, individual and collaborative production, replenishment and delivery plans. Enterprises of automotive pilot will

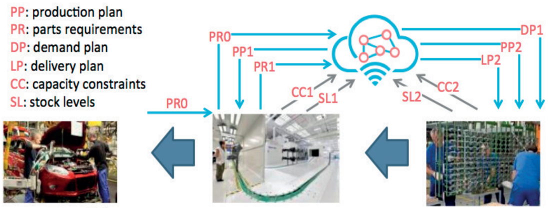

Figure 2. C2NET Automotive Pilot.

share relevant information and will use the C2NET advanced algorithms to optimise production, supply and replenishment plans.

4.1. Problem Description

The research work carried out in these papers (Andres *et al.,* 2016a*,* 2016b, 2017, 2018; Orbegozo *et al.,* 2018) identified concrete solutions proposed in the literature to support the (i) individual production, replenishment and delivery planning; and (ii) collaborative production and replenishment plans, collaborative production and delivery plans, collaborative replenishment and delivery plans and collaborative replenishment, production and delivery plans. The literature plans were compared with the real requirements collected from the industry. In this regard, the needs of all the industrial pilots of C2NET project are analysed. The comparison allowed identifying some gaps between the literature and the industrial needs regarding individual and collaborative replenishment, production and distribution planning.

This paper focuses on the Automotive Pilot, and a set of plans, with interest of study due to their complexity and the lack of automation (so far are manually solved), have been identified within the Automotive Pilot, including the injection replenishment plan, emergency replenishment plan, master injection production plan, spare parts production plan, injection scheduling plan, painting scheduling plan and delivery plan. Furthermore, among the recorded plans there have been identified which ones are willing to be collaboratively performed within the two enterprises covering the pilot, according to the enterprises needs and criteria.

C2NET project has focused on identifying the needs and requirements of both companies in the Automotive Pilot when dealing with their production, replenishment and delivery plans.

Based on the requirements' analysis of the first and second-tier suppliers of the Automotive Pilot (whose production is based on injection moulding) the need of a multi-machine injection moulding sequencing optimisation was detected for reducing the setup costs and forestalling product delays, by not only using the stocks, but also by obtaining a more efficient injection sequencing plan.

According to the needs identified in the enterprises of the Automotive Pilot, and considering the results of the literature carried out, it can be concluded that the algorithms found in the literature will require adaptations before they can be applied in the optimisation cases of the Automotive Pilot because both the amount and nature of the inputs, objectives and outputs have very low interdependence with the industry requirements.

In order to better understand the calculation of the multi-machine injection moulding sequencing plan in the automotive suppliers, the process carried out by second-tier supplier planner is explained next, in the same way as the enterprise computes it currently.

The second-tier supplier receives a new demand plan from the first-tier supplier. In order to fulfil the demand of the first-tier supplier, the company planner has to compute the quantity of products to produce, the moulds with the cavities of the demanded product, and the machines in to which setup the mould and carry out the injection process. The second-tier supplier planner has to schedule the products in a set of 20 different machines. In each machine can be setup a specific mould, which through the process of injection generates a specific product. The multi-machine injection moulding sequencing plan is calculated by the planner in a in a spreadsheet sequencing first one matching and considering the sequence of one machine after another. The second-tier supplier planner tries to minimise the products delayed, to the extent that the missing deliveries per million (MPM) equals zero. In the automotive sector, to deliver the products in the quantity and time periods demanded is a key factor, due to the OEM works in a Just in Time (JIT) regime. A delayed product could involve a stop in the production line of the OEM and consequently millenary losses. In order to avoid this problem, the second-tier supplier works in a 3 days of coverage, of the demand plan released by the first-tier supplier.

At the same time, the company planner tries to reduce as much as possible the inventory, but this is a hard task, due to the inventory is used to deal with the continuous changes on the demand, which is a common pattern in the automotive sector (Diaz-Madroñero *et al.,* 2018).

Although the second-tier supplier is interested in minimising the costs of the multi-machine injection moulding sequencing plan, no optimisation is performed and the process is manually solved. According to this, the main aim is to provide a MILP to optimally solve the multi-machine injection moulding sequencing plan in the second-tier supplier.

The main aim is to include the proposed MILP to compute the multi-machine injection moulding sequencing plan in the (C2NET OPT), connected with the continuous data collection services (C2NET DCF) and embedded in the Cloud Platform (C2NET CPL).

5. A multi-machine MILP for injection sequencing

A MILP is proposed to deal with a multi-machine injection moulding sequencing plan, which has 4 indexes for modelling: the products (*i*), moulds (*j*), machines (*k*) and periods (*t*). The parameters and decision variables are described in Table 1.

The objective function (Equation 1) minimises the sum of the cost of setting up the mould *j* in a machine *k*, the inventory and backorder costs of product *i*.

Table 1. Nomenclature of the multimachine MILP.

Index	
I	Set of products (p)
J	Set of moulds (o)
K	Set of machines (m)
T	Set of periods (t)
Parameters	
c_{ij}	Production rate of the product i using the mould j
ca_t	Capacity of production in hours for period t
d_{it}	Demand of product i during period t
$INVMAX_i$	Maximum available inventory capacity for product i
$INVMIN_i$	Minimum inventory for product i
INV_{i0}	Initial inventory of product i
ci_i	Inventory cost of product i
cst_i	Stockout cost of product i
cd_i	Delay cost of one unit of product i
cs_j	Setup cost of the mould *j*
n_j	Amount of mould *j* available
ns_t	Maximum amount of setups allowed in period *t*
Decision variables	
Y_{jkt}	1 if the mould j is producing products in the machine k in the period t, 0 otherwise
S_{jkt}	1 if the mould *j* starts producing products in the machine *k* in the period *t* and in period *t*-1 if it was another mould *j* setup in the machine *k*, 0 otherwise
P_{it}	Amount produced of product i in the period t
INV_{it}	Inventory level of product i at the end of period t
D_{it}	Delay amount of product i at the end of period t

$$Min z = \sum_j \sum_k \sum_t cs_j \cdot S_{jkt} + \sum_i \sum_t ci_i \cdot INV_{it} + \sum_i \sum_t cd_i \quad (1)$$

Constrains are presented in Equations 2 – 10:

In each period t one or any mould j can be producing

$$\sum_j Y_{jkt} \leq 1 \quad (2)$$

In each machine *k* it can only be setup the amount of moulds *j* available

$$\sum_k Y_{jkt} \leq n_j \quad \forall\, j, t \quad (3)$$

Production of product *i* in period *t*, constrained by the capacity

$$P_{it} = \sum_k \sum_j c_{ij} \cdot ca_t \cdot Y_{jkt} \quad \forall i, t \quad (4)$$

First activation of mould *j* in machine *k* at first period *t=1*

$$S_{jkt} = Y_{jkt} \quad \forall\, j, k, t = 1 \quad (5)$$

Setup restriction: 1 when the mould *j* in machine *k* is active in the period *t*, and it was not active at period (*t*-1), 0 if the mould *j* in machine *k*

$$S_{jkt} \geq Y_{jkt} - Y_{jkt-1} \quad \forall\, j, k, t > 1 \quad (6)$$

Mould *j* setups in machine *k* is limited by the maximum amount of setups allowed in period

$$\sum_k \sum_j S_{jkt} \leq ns_t \quad \forall\, t \quad (7)$$

Inventory balance and bounds

$$INV_{it} = INV_{i0} + P_{it} - d_{it} + D_{it} \quad \forall\, i, t = 1 \quad (8)$$

$$INV_{it} = INV_{it-1} + P_{it} - d_{it} + D_{it} - D_{it-1} \quad \forall\, i, t \neq 1 \quad (9)$$

$$INVMIN_i \leq INV_{it} \leq INVMAX_i \quad \forall\, i, t \quad (10)$$

The main index of the model is the mould *j*, allowing to sequence moulds in a multi-machine environment. The number of mould setups in each period is limited by the capacity constrains related to the availability of moulds (3).

The validation considers 3 different size of realistic data to verify the results, solving realistic problems in reasonable time. The small dataset (*i=2*, *j=2*, *k=2* and *t=2*) needs less than 1 sec to be optimised, the medium dataset (*i=29*, *j=10*, *k=18* and *t=14*) is solved in 60 s (GAP=1.7×10^{-5}). Finally, the large dataset (*i=100*, *j=100*, *k=18* and *t=50*) is computed in 18 h (GAP=0,168).

6. Conclusions

In this paper, the C2NET European H2020 Funded Project is described, focusing on its objectives, architecture, results and impacts resulting from the implementation of the results obtained: C2NET Cloud Platform.

The production planning problem has been identified within the Automotive Pilot, taking part in C2NET Project. The research carried out has allowed to state that to the best of our knowledge, the problem identified has not been addressed in the literature due to the particularities handled by the second-tier supplier analysed. In this regard, and with the aim of generating novel solutions in the scope of the C2NET OPT, a new MILP model for multi-machine injection moulding sequencing is proposed. The new model considers the demand backorders, the setups limits per time period and the security stocks defined by the second-tier supplier to face the demand variations to which it is subject. The validation of the MILP model has been performed with three sets of data: small, medium and large, in order to confirm the computational efficiency levels and corroborate its applicability in a real enterprise.

Future developments are lead to include new restrictions related with machine setups, route priorities in machines, and setup dependencies when performing carrying out a change over from one product to another. Moreover, it would be useful to include restrictions related with the materials requirement plan in order to sequence the final products, whose raw materials are available in the inventory. Finally, the proposed novel MILP model for multi-machine injection moulding sequencing will be implemented and validated in an enterprise, considering real data.

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References

Andres, B., Poler, R. (2016). A decision support system for the collaborative selection of strategies in enterprise networks. *Decision Support Systems, 91*, 113-123. https://doi.org/10.1016/j.dss.2016.08.005

Andres, B., Poler, R., Saari, L., Arana, J., Benaches, J.V., Salazar, J. (2018). Optimization Models to Support Decision-Making in Collaborative Networks : A Review, in: *Closing the Gap Between Practice and Research in Industrial Engineering, Lecture Notes in Management and Industrial Engineering*. 249-258. https://doi.org/10.1007/978-3-319-58409-6_28

Andres, B., Saari, L., Lauras, M., Eizaguirre, F. (2016a). Optimization Algorithms for Collaborative Manufacturing and Logistics Processes, in: Zelm, M., Doumeingts, G., Mendonça, J.P. (Eds.), *Enterprise Interoperability in the Digitized and Netwroked Factory of the Future*. iSTE, 167-173.

Andres, B., Sanchis, R., Lamothe, J., Saari, L., Hauser, F. (2016b). Combined models for production and distribution planning in a supply chain, in: Building Bridges between Researchers and Practitioners. *Book of Abstracts of the International Joint Conference CIO-ICIEOM-IISE-AIM* (IJC2016), 71.

Andres, B., Sanchis, R., Lamothe, J., Saari, L., Hauser, F. (2017). Integrated production-distribution planning optimization models : A review in collaborative networks context. *International Journal of Production Management and Engineering, 5*, 31-38. https://doi.org/10.4995/ijpme.2017.6807

Andres, B., Sanchis, R., Poler, R. (2016c). A Cloud Platform to support Collaboration in Supply Networks. *International Journal of Production Management and Engineering*, *4*, 5-13. https://doi.org/10.4995/ijpme.2016.4418

Camarinha-Matos, L.M., Afsarmanesh, H. (2008). *Collaborative Networks: Reference Modelling*. Springer International Publishing.

Camarinha-Matos, L.M., Afsarmanesh, H. (2005). Collaborative networks : a new scientific discipline. *Journal of Intelligent Manufacturing*, *16*(4-5), 439-452. https://doi.org/10.1007/s10845-005-1656-3

Commission, E. (2012). European Comission [WWW Document]. Eur. Compet. Report. 2012. Reaping Benefits Glob. Comm. Staff Work. Doc. SWD(2012)299 Final.

Diaz-Madroñero, M., Mula, J., Andres, B., Poler, R., Sanchis, S. (2018). Capacitated Lot-Sizing and Scheduling Problem for Second-Tier Suppliers in the Automotive Sector, in: *Closing the Gap Between Practice and Research in Industrial Engineering*. Springer International Publishing, 121-129. https://doi.org/10.1007/978-3-319-58409-6

European Commission (2008). Work Programme. Cooperation Theme 4 Nanosciences, Nanotechnologies, Materials And New Production Technologies – NMP (European Commission C (2007) 5765 of 29 November 2007).

European Commission (2013). Fact and figures about the EU's Small and Medium Enterprise (SME) [WWW Document].

Lauras, M., Lamothe, J., Benaben, F., Andres, B., Poler, R. (2015). Towards an Agile and Collaborative Platform for Managing Supply Chain Uncertainties. In: *International IFIP Working Conference on Enterprise Interoperability*, 64–72. https://doi.org/10.1007/978-3-662-47157-9_6

Orbegozo, A., Andres, B., Mula, J., Lauras, M., Monteiro, C., Malheiro, M. (2018). An Overview of Optimization Models for Integrated Replenishment and Production Planning Decisions, in: *Closing the Gap Between Practice and Research in Industrial Engineering, Lecture Notes in Management and Industrial Engineering*, 239-247. https://doi.org/10.1007/978-3-319-58409-6_27

