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Published in:
Procedia CIRP

DOI (link to publication from Publisher):
10.1016/j.procir.2021.11.093

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

Citation for published version (APA):
Kjeldgaard, S., Jorsal, A. L., Albrecht, V., Andersen, A-L., Brunø, T. D., & Nielsen, K. (2021). Towards a model for evaluating the investment of reconfigurable and platform-based manufacturing concepts considering footprint adaptability. *Procedia CIRP*, *104*, 553-558. https://doi.org/10.1016/j.procir.2021.11.093

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 104 (2021) 553–558

www.elsevier.com/locate/procedia

54th CIRP Conference on Manufacturing Systems

Towards a model for evaluating the investment of reconfigurable and platform-based manufacturing concepts considering footprint adaptability

Stefan Kjeldgaard[a],*, Andreas Leon Jorsal[a], Vanessa Albrecht[a], Ann-Louise Andersen[a], Thomas Ditlev Brunoe[a], Kjeld Nielsen[a]

[a] *Aalborg University, Department of Materials and Production, Fibigerstraede 16, 9220 Aalborg East, Denmark*

* Corresponding author. Tel.: +45 24800604; *E-mail address:* stefank@mp.aau.dk

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Abstract

The capital goods industry is characterized by intensified competition and increased fragmentation of demand. Consequently, manufacturers are required to handle higher variety at lower cost with rapid responsiveness. Reconfigurable manufacturing shows potential to meet these requirements through efficient functionality conversion of modularized equipment for increased ability to adapt the footprint to achieve cost-improvements and competitive advantage. However, current models for evaluating the investment of reconfigurable manufacturing concepts lack consideration of footprint adaptability. Therefore, this paper presents a model considering reconfigurability investments and footprint, which is applied on a case at a Danish manufacturer of capital goods for the energy sector.

Keywords: Changeable manufacturing; Reconfigurable manufacturing; Concept evaluation; Footprint adaptability; Capital goods

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1. Introduction

The globalized manufacturing environment of the twenty-first century is characterized by intensified competition in uncertain markets with increased fragmentation of demand [1]. Consequently, manufacturers are required to handle a high variety of products with frequent new introductions and short life-cycles at a low cost to sustain competitiveness [1, 2]. In this context, dedicated manufacturing systems have high risk of low capacity utilization and life-cycle misalignment [1, 3-5] due to their dedicated functionality limiting their reusability [6].

In contrast, reconfigurable manufacturing systems (RMS) have been proposed as means to accommodate the outlined requirements, as they are designed for rapid conversion of functionality and scaling of capacity to exactly what is needed, exactly when needed [1, 7]. This dynamic capability is enabled by a set of characteristics and can be implemented on several levels across the manufacturing hierarchy [1, 5, 6, 8]. However, no matter the implementation level, reconfigurability involves a modular architecture which enables the rearrangement or change of system constituents for reconfiguration [5, 9], where the time and effort spent during reconfiguration is decreased by integrability [4, 7, 10], mobility [4, 8, 10] and reusability of modules. Moreover, it is implied that the functionality range of RMS is designed for a family of product variants [3, 10], which can be supported by co-platforming [11]. In turn, the platform of RMS constitutes the common reusable modules from which a set of derivative system variants can be configured [11].

With regards to methodologies for development of RMS, there is a lack of research on evaluation of conceptual designs [12]. In turn, this limits manufacturers in transitioning towards RMS, as the unstructured and subjective approaches applied in practice are insufficient for intercepting relevant aspects of reconfigurability [12]. Making matters worse, evaluation of design concepts constitutes an essential and critical part of system development [13, 14], as 80% of the resources required to develop a system are committed by decisions made in the

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10.1016/j.procir.2021.11.093

initial design activities [15], where a wrong choice of concept rarely can be recouped in detailed design [16].

For RMS development, some evaluation methods have been proposed, e.g. based on economic and strategic objectives [17], based on scenario analysis and cost evaluation [18], or based on qualitative comparison [19]. However, most of these focus on general justification of RMS compared to other paradigms and are limited in terms of applicability in evaluation of actual design concepts and critical trade-offs, especially concerning support for real world design problems and the industrial application [12]. Consequently, the methods do not consider the potential of RMS on higher manufacturing levels, such as the ability to adapt the manufacturing footprint. In this regard, footprint adaptability is defined as the ability to make rapid and economic changes of functionality and capacity across a set of factories to efficiently match changing demand requirements.

For manufacturers in the capital goods industry transitioning towards RMS, footprint adaptability is crucial to consider when evaluating the investment of RMS design concepts [20, 21]. Manufacturers of capital goods operate with a global footprint of factories where changes to the footprint are needed (i) as localized manufacturing is required to an increasing extent to qualify for orders through competitive tendering schemes (ii) as capital goods are large scale in terms of physical dimensions, where the high cost of transportation is increasing [20, 21]. Previous research in this context, indicate that RMS can enable rapid and cost-efficient response to changes in production mix on a factory level, which in turn, increases the ability to adapt the manufacturing footprint to achieve cost-improvements and a significant competitive advantage [20, 21].

In order to mitigate the stated deficiencies related to research on evaluation of conceptual RMS design and to support global manufacturers of capital goods in the transition towards RMS, the following research question has been formulated:

- How can a supportive model be constructed, which can be applied in initial phases of manufacturing system development for evaluating the investment of reconfigurable and platform-based design concepts considering footprint adaptability?

The remainder of the paper is structured as follows:

- Section 2 outlines the applied research methodology, followed by the industrial case and modelling approach.
- Section 3 present the proposed model, followed by the results from applying the model to the industrial case.
- Section 4 presents a discussion of the model and results, followed by the theoretical and industrial implications.
- Section 5 provides conclusive remarks.

2. Method

In order to address the research question outlined above, design science is applied as research methodology. This choice is reasoned as the research question is partially derived from a wicked problem present in a specific industrial context, which requires applied research and empirical data to produce novel solutions with practical utility [22].

The design science methodology consists of three iterative cycles (i.e. rigor cycle, relevance cycle and design cycle) with six activities, that interconnects the contextual environment and knowledge base with the design science research [22]. The research presented in this paper, follows the activities devised by the methodology, which are listed below.

- Identify requirements (from contextual environment)
- Draw inspiration (from knowledge base)
- Construct model (during design science research)
- Evaluate model (during design science research)
- Test model (in contextual environment)
- Add research contributions (to knowledge base)

By applying the design science methodology, the research is empirically driven with the objective to produce research results that are applicable in practice to support the process of developing reconfigurable and platform-based manufacturing systems. An industrial company was involved throughout the activities, and supported to identify the requirements, evaluate the model and retrieve data to test the model.

2.1. Industrial case

The case company is a global manufacturer of capital goods for the energy sector. The product has a modular architecture, where the main product module is manufactured using make-to-stock or make-to-order. Recently, the company has initiated a transition towards reconfigurability in manufacturing of the product module, where the primary equipment is in focus as it is the bottleneck with respect to the capacity and functionality of the manufacturing lines at the factories. This bottleneck refers to the equipment (i) being the limiter of production throughput (ii) being dedicated to single variants, where the factories have limited physical space for multiple instances of equipment, as it is large-scale in terms of physical dimensions, which is also the case for the product module itself.

For the manufacturing of the product module, the company operates with a set of factories across a global footprint to fulfill global demands as (i) localized manufacturing can be required to qualify for orders (ii) the high cost of transporting the large-scale modules is increasing. Combining these factors with increasingly fluctuating demand in terms of variety, volume, timing, and location, creates a context where each factory's unique range of functionality and capacity has a risk of mismatching the local demands they are most suitable to fulfill.

Based on a pilot-project at the lead-factory, initial results indicate that the reconfiguration time and capital cost of lines where the equipment is installed can be decreased by applying modular and platform-based design to enable reconfigurable equipment with reusability of modules across configurations. In continuation, the reconfigurable equipment shows potential to enable rapid and cost-efficient response to changes in production mix on a factory level, which in turn, increases the ability to adapt the manufacturing footprint to achieve cost-improvements and a significant competitive advantage. To capitalize on the initial results and the related potential, the company is in progress of co-developing reconfigurable and platform-based equipment with sectional modular architecture and convertible functionality for the manufacturing of four product module variants sharing similar architectural and geometrical structures. As part of this, the company needs to evaluate the investment of reconfigurable and platform-based equipment design concepts in contrast to the currently applied dedicated equipment design concept, with consideration of the impact on footprint adaptability and total cost.

2.2. Modelling approach

Based on the research question stated in Section 1 derived from the requirements of the industrial case, a model is required to evaluate the investment of reconfigurable and platform-based manufacturing equipment design concepts in contrast to the currently applied dedicated equipment, with consideration of footprint adaptability and total cost. To support this, the model requires integration of the following decisions:

- reconfiguration and production on line and equipment level
- production, inventory, and transportation on factory level
- allocation of equipment and demand across the footprint

To account for the interplay between decisions and related trade-offs, monolithic planning models that integrate decisions across hierarchical levels are proposed by Asmussen et al. [23] as a means to sufficiently evaluate the investment in production assets, which concerns the equipment design concepts within the context of the case. Monolithic planning models integrate such hierarchical decisions through large-scale mathematical programming to derive an optimum solution [23]. For the case, the unique input parameters of each design concept were iteratively applied to such a model to derive a monolithic plan with optimal total cost for each design concept. Subsequently, the total cost of the plan for each concept was comparatively evaluated, to select the suitable concept for detailed design.

The proposed model was formulated in Microsoft Excel using the OpenSolver add-in, as it enables visualization to aid debugging and dissemination of the model's construction. The model was solved using the Gurobi Engine as it can (i) handle a vast amount of decision variables (ii) utilize multiple CPU cores and a variety of algorithms to rapidly solve model iterations compared to other solvers.

2.3. Data collection

A combination of field- and desk research was applied across a period of 4 months to: (i) identify the problems and opportunities of the industrial case company (ii) identify the requirements for the construction and utility of the model (iii) retrieve inputs for model testing. Specifically, manufacturing operations of the lead-factory were observed with a process, resource and spatial perspective. Furthermore, semi-structured interviews were conducted with several stakeholders from: product engineering, manufacturing engineering and supply chain planning. Finally, archival data were extracted from the ERP system, spreadsheets, and presentations.

3. Results

3.1. Proposed model

An Integer Programming (IP) monolithic planning model is proposed for concept evaluation, which integrates decisions on equipment investments, reconfiguration, production, inventory and transportation across the factories and lines of the footprint to meet the customer regions' demanded variety, volume and timing hereof, at the lowest possible total cost.

The model contains decision variables, auxiliary variables, constraints, input parameters, output parameters and objective function. The decision variables are provided in Table 1, and are interconnected by the auxiliary variables provided in Table 2, through a set of variable calculations and constraints. The decision- and auxiliary variables are noted with uppercase *b* and *i*, to indicate their constraint of being binary or integer. Several input parameters are dependent on the design concept applied to the model, and these are provided in Table 3, whereas the input parameters independent of applied concept, are provided in Table 4. The output parameters are provided in Table 5 and the objective function is minimization of total cost.

Table 1. Decision variables.

Variables	Description
$\text{Transportation}^{i}$	Transported volume of variant *v* from factory *f* to region *r* in period *t*
$\text{Production}^{\text{b}}$	Production of variant *v* on line *l* at factory *f* in period *t*
$\text{Reconfiguration}^{\text{b}}$	Reconfiguration from variant v^{f} to variant v^{t} on line *l* at factory *f* in period *t*
$\text{Module}_{\text{x}}^{\text{i}}$	Quantity of equipment module *x* in factory *f*
$\text{Module}_{\text{y}}^{\text{i}}$	Quantity of equipment module *y* in factory *f*
$\text{Module}_{\text{z}}^{\text{i}}$	Quantity of equipment module *z* in factory *f*

Table 2. Auxiliary variables.

Variables	Description
$\text{Inventory}^{\text{i}}$	Stored volume of variant *v* in factory *f* in period *t*
$\text{Production}^{\text{i}}$	Produced volume of variant *v* in factory *f* in period *t*

$\text{Production}^{\text{i}}$ is calculated as $\text{production}^{\text{b}}$ *times* capacity. $\text{Inventory}^{\text{i}}$ in period *t* is calculated as inventory in period *t-1* *plus* $\text{production}^{\text{i}}$ in period *t minus* $\text{transport}^{\text{i}}$ in period *t*.

The sum of $\text{transportation}^{\text{i}}$ of each variant *v* in each period *t* for all factories *f* and regions *r* is constrained to (i) equal demand (ii) be less or equal to $\text{inventory}^{\text{i}}$. These constraints ensure that (i) the demand is supplied with the required variant, in the required volume, in the required period (ii) factories have sufficient inventory to transport the required supply. The sum of $\text{production}^{\text{b}}$ of each variant *v* for all factories *f*, lines *l* and periods *t* is constrained to equal one. This constraint ensures that only one variant can be produced on each line per period. Module_{x}, module_{y} and module_{z} are each constrained to be greater than or equal to the sum of $\text{production}^{\text{b}}$ of each variant *v* for all factories *f*. This constraint ensures that each factory has invested in the required quantity of equipment modules to possess the required functionality and capacity to produce the required variant and volume of the decided production mix.

Table 3. Input parameters (dependent on design concept)

Parameters	Description
Reconfiguration time	Number of periods *t* for reconfiguration from variant v^f to variant v^t on line *l*
Reconfiguration cost	Labor and transport cost of reconfiguration from variant v^f to variant v^t on line *l*
Module$_x$ cost	Capital cost of equipment module *x*
Module$_y$ cost	Capital cost of equipment module *y*
Module$_z$ cost	Capital cost of equipment module *z*

Table 4. Input parameters (independent of design concept)

Parameters	Description
Demand	Demand volume of variant *v* from region *r* in period *t*
Transport cost	Transport cost of variant *v* from factory *f* to region *r*
Inventory cost	Inventory cost of variant *v* in factory *f*
Production cost	Production cost of variant *v* in factory *f*
Capacity	Production volume of line *l* at factory *f* in period *t*

Table 5. Output parameters

Parameters	Calculation
Total cost	total transport cost *plus* total inventory cost *plus* total production cost *plus* total reconfiguration cost *plus* total equipment cost
Total transport cost	*Sum* of transportation^i *times* transport cost for all variants *v*, factories *f*, regions *r* and periods *t*
Total inventory cost	*Sum* of inventory^i *times* inventory cost for all variants *v*, factories *f* and periods *t*
Total production cost	*Sum* of production^i *times* production cost for all variants *v*, factories *f* and periods *t*
Total reconfiguration cost	*Sum* of reconfiguration^b *times* reconfiguration cost for all variants v^f, variants v^t, lines *l*, factories *f* and periods *t*
Total equipment cost	*Sum* of module$_x^i$ *times* module$_x$ cost for all factories *f*, *plus sum* of module$_y^i$ *times* module$_y$ cost for all factories *f*, *plus sum* of module$_z^i$ *times* module$_z$ cost for all factories *f*

3.2. Model inputs (in case)

The case indices applied to the model are 52 time periods, 4 variants, 6 regions, 7 factories, 22 lines, 4 module$_x$, 4 module$_y$, 4 module$_z$ and 25 reconfiguration options $(5v^f \times 5v^t)$.

An overview of equipment design concepts' configuration of module variants for each product variant is provided in Table 6. Also included in Table 6, are the equipment design concepts' performance on (i) reconfiguration time (i) reusability of modules, across configurations. Note that module reusability has a negative relationship with the (i) capital cost required to perform reconfigurations (ii) time and cost of reconfigurations.

The DE (dedicated equipment) concept used four variants of module$_x$, module$_y$ and module$_z$ for four configurations. The RE (reconfigurable equipment) 1 concept used a common module$_x$ as platform and four variants of module$_y$ and module$_z$ for four configurations. The RE 2 concept used a common module$_x$ and module$_z$ as platform and four variants of module$_y$ for four configurations. The RE 3 concept used a common module$_x$ as platform and two variants of module$_y$ and module$_z$ which are partially common across four configurations.

Table 6. Configuration of equipment module variants across product module variants for each design concept and related performance of reconfigurability

	DE	RE 1	RE 2	RE 3
Variant 1	AAA	AAA	AAA	AAA
Variant 2	BBB	ABB	ABA	AAB
Variant 3	CCC	ACC	ACA	ABA
Variant 4	DDD	ADD	ADA	ABB
Module reusability (*%*)	0	60	70	60/70/90
Reconfiguration time (*t*)	14	6	4	6/4/2

For confidentiality purposes, the input parameters of the case related to demand, costs and capacity are not provided. However, characteristics of demand are provided in Table 7.

Table 7. Characteristics of demand input

	Pattern	Volume	Timing	Region
Variant 1	Stable	High	Continuous	Global
Variant 2	Boom and bust	Low	Periodically	Local
Variant 3	Hockey stick	Medium	Periodically	Local
Variant 4	Unstable	Medium	Periodically	Global

3.3. Model results (in case)

Applying the input parameters of the case to the model yielded feasible and optimal plans for each design concept, with respect to allocation of demand and resources across the manufacturing footprint to achieve lowest total cost. A comparison of costs is provided in Table 8, where the costs of RE concepts' plans are calculated as the relative change from the costs of the DE concept's plan set at index = 100.

The comparison shows that RE 1, RE 2 and RE 3 reduce total cost with 1%, 1.2% and 1.8% respectively. This reduction of total cost is mainly driven by a reduction of total reconfiguration cost and total equipment cost, which carries a trade-off with respect to an increase of total production cost in addition to an increase of total transport cost for RE 3.

This trade-off is made for RE concepts' plans as the solver computes it more cost-efficient to reconfigure equipment once installed, as opposed to the DE concept's plan where additional equipment is installed at factories with lower production and transport cost to satisfy the demand. The increased number of installed equipment for the DE concept's plan, in contrast to the increased number of equipment reconfigurations for the RE concepts' plans, is provided in Table 8 as well.

Table 8. Comparative results of solving the IP model for each design concept

Parameters	DE	RE 1	RE 2	RE 3
Total cost	**100**	**99.0**	**98.8**	**98.2**
Total transport cost	100	99.4	99.4	102.1
Total inventory cost	100	98.8	101.1	99.7
Total production cost	100	100.3	100.3	100.9
Total reconfiguration cost	100	92.1	91.8	84.3
Total equipment cost	100	95	93.4	86.9
No. of equipment	22	19	19	18
No. of equipment reconfigurations	0	4	4	5

4. Discussion

4.1. Model results (in case)

The results of applying the model to the case, indicate that the design concepts of reconfigurable equipment with higher reconfiguration efficiency (higher module reusability and lower reconfiguration time) can generate monolithic plans with comparatively lower total cost. In turn, this indicates a positive relationship between cost-improvements and reconfiguration efficiency. This is reasoned as the design concepts with higher reconfiguration efficiency increase the feasibility of:

- operating with a lower number of lines and equipment
- transporting from factories with proximity to demand

However, a trade-off is made for RE 3 with respect to these two sub-objectives, which is indicated by the comparatively lower total equipment cost and higher total transportation cost. The trade-off is made for RE 3 as the solver computes that a lower total cost can be achieved by, reconfiguring installed equipment at a factory, as opposed to installing additional equipment at a factory with closer proximity to demand. This additional reconfiguration is not made when applying the other RE concepts, as the comparatively lower reconfiguration time makes it infeasible to satisfy the demand requirements in time, thus requiring additional equipment to be installed.

Nevertheless, the comparative results indicate that the RE 3 design concept is most suitable to select for detailed design.

4.2. Practical and theoretical implications

The industrial application of the model presented in this paper, reflects its applicability in evaluation of actual design concepts of reconfigurable and platform-based manufacturing systems and the related trade-offs in terms of the impact on footprint adaptability and total cost. In the industrial company, the model application was used for evaluating:

- the investment feasibility of RMS in contrast to DMS
- the extent of reconfigurability to embody in equipment

In addition to the practical relevance of the model and its application to aid an industrial transition towards RMS, the model provides an example on how design concepts of RMS can be comparatively evaluated while considering the impact on footprint adaptability and total cost. As the model supports this, the research presented in this paper provides a theoretical contribution that bridges the research gap outlined in Section 1 related to evaluation of conceptual designs of RMS. Moreover, the case results provide novel insights to the literature body on RMS. This is reasoned as RMS has mostly been addressed and explored on a shop floor level in previous research, with limited consideration of context-specific drivers and potentials of RMS on higher manufacturing levels and the resulting applications and performance [20, 21]. As the lack of research on higher levels of manufacturing is one of the main challenges in the industrial implementation of RMS [24], the contribution of this paper aids to mitigate this challenge as well.

With regards to generalization of the proposed model, it is applicable in industrial contexts where manufacturers require consideration of footprint adaptability in the evaluation of the investment of RMS and design concepts hereof. Consequently, the manufacturers would operate with a footprint and a need for changes to it. The drivers for footprint changes are context-specific and can arise from internal or external triggers [21]. Examples of these drivers include changes in: demand, lead-time requirements, localization requirements, transportation costs, labor costs, trade regulations, trade tariffs and resource availability (e.g. due to supply or labor constraints) [1, 20, 21]. Examples of industrial contexts where manufacturers operate with the need for footprint changes includes the automotive- and capital goods industry (e.g. energy, aerospace, machinery).

4.3. Model limitations

The model proposed in this paper has been validated in an industrial case, where data collection required the researchers' involvement. From the validation, two limitations arose related to the model inputs, in terms of the configured time horizon and uncertainty in demand, which is outlined in the following.

The case-company operates with a yearly planning horizon where functionality and capacity are allocated across the footprint by means of investments in equipment, to match forecasted demand requirements with minimal total cost. To match this planning horizon, the model was configured with a time horizon of 52 weeks. However, this limited time-horizon imposes issues for a proper evaluation of the design concepts' impact on footprint adaptability and total cost. This is partially reasoned as the equipment is designed with a technical life-time of several years, that impose a risk of life-cycle misalignment and low capacity utilization as the demand and life-cycle of product variants are uncertain. Consequently, by disregarding demand uncertainty throughout product variants' life-cycles, bounded rationality is imposed to the model and the evaluation. Exemplified, the performance of RE 3 is especially dependent on demand as the reconfiguration efficiency differs depending on the reconfiguration to be made, as the design concept applies variants of modules which are partially common and reusable across equipment configurations. In a scenario, where variant 4 has a steady demand at high volume, the performance of RE 3 would presumably be less than that of RE 2 as the latter has greater efficiency in reconfiguration between variant 1 and 4. Thus, the lack of testing additional scenarios of demand across a longer time-time horizon, can implicate the results to such an extent that unsuitable concept is selected for detailed design. However, as the reconfigurable concepts are designed to be resilient with respect to coping with demand uncertainty at a comparatively lower total cost, the testing of additional demand scenarios across a longer time-horizon would presumably still indicate a comparatively lower total cost of the reconfigurable design concepts in contrast to the dedicated design concept.

This latter indication is supported by Andersen et al. [12] stating *"increased uncertainty regarding demand scenarios makes changeability more attractive and feasible"*. In a similar vein, stochastic demand parameters and life-time changeability requirements are proposed to be considered when evaluating the investment of RMS and design concepts hereof [12], which can mitigate the mentioned limitations of the proposed model.

5. Conclusion and future work

In this paper, a model for evaluating the investment of reconfigurable and platform-based design concepts considering footprint adaptability has been proposed as a means to support initial phases of manufacturing system development. The model was created through applied research that is empirically driven by a case at an industrial manufacturer with respect to: (i) identification of requirements (ii) retrieval of inputs for validation and implementation. The requirements necessitated the model to account for the interplay between decisions and trade-offs across manufacturing levels, to evaluate the design concepts' impact on footprint adaptability. The design concepts were applied iteratively to the model to derive a monolithic plan with minimal total cost for each design concept, which were subsequently comparatively evaluated. The results showed that the design concepts with higher module reusability and lower reconfiguration time can generate monolithic plans with comparatively lower total cost through increased footprint adaptability. Based on the results, the design concept applying partial commonality of module variants across configurations, proved to be the most suitable to select for detailed design.

The research presented in this paper provides a novel contribution which aids (i) mitigating the deficiencies related to research on evaluation of design concepts of reconfigurable manufacturing systems, (ii) supporting the industrial transition towards reconfigurable manufacturing systems. With regards to generalization, further research should seek to validate the model by applying it to additional cases. Moreover, it is proposed to configure the model with a sufficiently long time-horizon and several scenarios of demand to increase the validity of the results generated by the model.

Acknowledgements

The research presented in this paper is conducted within the Manufacturing Academy Denmark (MADE) research program, funded by the Innovation Fund Denmark.

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