Enabling adaptability and resilience of a global production network: A model to evaluate capital and operational expenses of reconfigurable production systems

Kjeldgaard, Stefan; Andersen, Ann-Louise; Brunø, Thomas Ditlev

Published in:
Journal of Manufacturing Systems

DOI (link to publication from Publisher):
https://doi.org/10.1016/j.jmsy.2022.12.003

Publication date:
2023

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

Citation for published version (APA):
Kjeldgaard, S., Andersen, A-L., & Brunø, T. D. (2023). Enabling adaptability and resilience of a global production network: A model to evaluate capital and operational expenses of reconfigurable production systems. *Journal of Manufacturing Systems*, *66*, 142-162. https://doi.org/10.1016/j.jmsy.2022.12.003

Journal of Manufacturing Systems 66 (2023) 142–162

Contents lists available at ScienceDirect

Journal of Manufacturing Systems

journal homepage: www.elsevier.com/locate/jmansys

Enabling adaptability and resilience of a global production network: A model to evaluate capital and operational expenses of reconfigurable production systems

Stefan Kjeldgaard [*], Ann-Louise Andersen, Thomas Ditlev Brunoe

Department of Materials and Production, Aalborg University, Fibigerstraede 16, Aalborg 9220, Denmark

ARTICLE INFO

Keywords:
Global production network
Reconfigurable manufacturing
Changeability
Investment analysis
Economic justification

ABSTRACT

The objective of this paper is to construct and apply a model to evaluate the expected performance impact with respect to capital and operational expenses of reconfigurable designs of production systems within a global production network. The case results suggest that reconfigurable production systems improve the operational and economic performance, especially the capital and transportation expenses, by facilitating increased adaptability and resilience of the global production network. A major conclusion is the importance of considering the drivers and potentials on the network level in quantitative empirical models for the economic evaluation of reconfigurable production systems in industrial cases.

1. Introduction

In the current industrial environment, global production networks (GPNs) need to be adaptable and resilient to changing and disruptive conditions in dynamic and uncertain contexts [1–5]. Globalization has in recent decades created fierce competition, turbulence in markets, and fragmentation of demand [6]. Moreover, globalization has shaped the decentralization to distributed production networks which is driven by resource scarcity, transport costs, requirements for localization and responsiveness [2]. More recently, the urgency and the scale of disruptions have increased due to the emergence of black swan events [1,5]. This includes natural disasters, logistical blockages, wars, and pandemics. Implications include (i) temporary and extended shutdowns or reassignments of factories due to lack of materials and labor [1,7], and (ii) impaired supply capability and localization needs due to transport restrictions and national protectionism [1].

GPNs consist of geographically distributed production entities with different roles that are arranged in a certain structure with vertical and horizontal dimensions [2,8]. The structure forms interrelations with certain patterns across upstream and downstream entities, with respect to the supply and demand of products and production systems where the global patterns imply that logistics has an equally important role [2,8]. Meyer et al. [8] distinguish between five network phenotypes: world factory, local for local, hub and spoke, chain, and web structure. The latter enables all factories to produce all products, merges the strengths of centralization and localization, and it can cope with demand fluctuations and level capacity utilization. The unique capabilities of web structures facilitate GPNs adaptability and resilience and it is therefore suggested as the phenotype of the future [2]. It is even the most common phenotype today [8] which is estimated to account for a share of $\geq 30\%$ in industry [9].

In response to the outlined drivers, reconfigurability of production systems is increasingly relevant [1,10], as they can facilitate adaptability and resilience of GPNs [4,11,12] to unexpected scenarios [1]. Reconfigurability is a tactical and dynamic capability of production systems to convert functionality and scale capacity with reasonable effort across a family of similar products or parts [1,13]. This capability is enabled by a design architecture that facilitates exchanging and integrating customized system modules to a common platform [13–15]. The capability contrasts with the traditional production paradigms of (i) dedicated systems with functionality and capacity for one product and its counterpart (ii) flexible systems with a wide a priori functionality range for more products, albeit with capacity for low volumes [6,15].

Although reconfigurability has been acknowledged as an increasingly relevant paradigm by scholars throughout the last 20 years [13,16], the widespread implementation in industry lacks [10,17] despite practitioners' recognition of its benefits [10]. There has been extensive research on the design of reconfigurable production systems, whereas

---

[*] Corresponding author.
E-mail address: stefank@mp.aau.dk (S. Kjeldgaard).

https://doi.org/10.1016/j.jmsy.2022.12.003
Received 16 June 2022; Received in revised form 26 August 2022; Accepted 5 December 2022

there is a lack of research on the related evaluation during design and operation [10,17–20]. This comprises models to evaluate the expected performance in terms of capital expenses and operational expenses [1, 16]. The evaluation is critical in production development in order to compare the feasibility of system designs before implementation [21,22] where it is near-impossible to mitigate principal flaws of early design decisions [16]. In practice, the relevance of evaluation is increased by the need to secure the scarce financial support and managerial commitment to advance the development [10,20]. Moreover, it is often difficult to justify investments in reconfigurability [23] as the traditional approaches are unsuitable to capture the benefits [22] which is a barrier in the transition [17].

A key issue for the evaluation, is a lack of research on the impact of reconfigurable systems on the performance of GPNs [4,10]. It has increased the gap to industrial contexts [24], which is critical due to the importance of GPNs in the economy [2] and as reconfigurable systems can facilitate adaptability and resilience [11,12]. This issue is also generally present in the research area of reconfigurability where the network level has been largely neglected [12,25,26], although potentials have been identified [27–29]. This imposes a challenge for the industrial implementation [30]. Therefore, to resolve these gaps and support industry, the objective of this paper is to construct and apply a model to evaluate the expected performance impact, with respect to capital and operational expenses of reconfigurable designs of production systems within a global production network.

In Section 2, literature on evaluation models is reviewed and compared to derive research gaps. The proposed model is presented with constituents and relations in Section 3, which is supported by the application method in Section 4. The industrial case and the collection of data is outlined in Section 5, whereas the graphical and numerical results of the case application are provided in Section 6. The theoretical and practical implications of the model and the case results are discussed in Section 7, whereas conclusions are given in Section 8.

2. Literature review

Reconfigurability is a complex and multi-dimensional capability [18, 27,31] as it can be embodied in many ways to various extents with context-specific potentials [16,23,26]. Consequently, the design evaluation is inherently complex which is increased by uncertainty and co-evolution of products and production systems [21]. Due to the complexity, a sufficient evaluation requires simulation or optimization models, especially in real cases [10,24] and with a scope of GPNs [2]. These types of models, within state-of-the-art, have been identified by Kjeldgaard et. al. [32] which this review builds upon. In the following sections, the models are outlined, classified, and compared to derive research gaps.

Table 1
Models to evaluate reconfigurable production systems and their related publication and classification information.

#	Author	Iterations	Year	Scope
1	Kuzgunkaya et al.	[33]	2008	System
2	Andersen et al.	[34]	2018	System
3	Bortolini et al.	[35,36]	2019, 2021	System
4	Niroomand et al.	[37,38]	2012, 2014	Factory
5	Gyulai et. al.	[39–41]	2014, 2017	Factory
6	Wörsdörfer et al.	[42]	2017	Network
	Becker et al.	[43,44]	2018	
7	Guo et al.	[45]	2018	Network
	Tian et al.	[46]	2019	
8	Kjeldgaard et. al.	[47]	2021	Network
9	Epureanu et al.	[11]	2021	Network

2.1. Outline and classification of models

The identified models are provided in Table 1, which lists the authors, the sources, the year of publication, and the classified scope. Moreover, several references are included in the table for some authors, if the reviewed model is published in multiple linked iterations. Furthermore, some models have also been expanded upon by another set of authors i.e. model 6 and model 7. The scope refers to the level of the production hierarchy that is being considered. The scope can be a production system, a factory with multiple systems, or a network with multiple factories and systems. The models will be outlined in the following subsections within their classified category of scope.

2.1.1. Models with a system scope

The model by Kuzgunkaya et al. [33] has the purpose to justify the lifetime investment of reconfigurable or flexible systems. The scope covers a system of machines that can be reconfigured with modules to execute production tasks of products to satisfy demand. LP (Linear Programming) is used to maximize the net present value of (i) revenue: sales of products and salvage of machines, (ii) capital expenses: investment of machines and modules, (iii) operational expenses: reconfiguration cost of machines, outsourcing costs of products, variable and fixed costs on machines.

The model by Andersen et al. [34] has the purpose to evaluate the investment feasibility of system designs: reconfigurable, flexible, or dedicated. The scope covers a system, that can be changed in functionality and capacity, to enable production of products to satisfy the demand. Moreover, it considers maintenance and occupied space of systems. The model uses discounted total cost that covers (i) capital expenses: investment in system expansions (ii) operational expenses: fixed costs of occupied shop-floor area, the cost of labor during the production of products along with the downtime and maintenance of the system.

The model by Bortolini et al. [35,36] was made in two iterations with the purpose to evaluate the performance of reconfigurable systems. The scope covers a system of cells with machines wherein modules can be reconfigured to execute production tasks of imposed batches of parts. The latter model considers scarcity of system modules [36] as opposed to being available in an infinite amount [35]. LP is used to minimize (i) the (dis-)assembly time of machines and (ii) the inter-cellular travel time of modules and parts.

2.1.2. Models with a factory scope

The model by Niroomand et al. [37,38] was made in two iterations and has the purpose to optimize the allocation of capacity investments among reconfigurable, dedicated, or flexible systems in various scenarios. The scope covers a factory with systems that can be reconfigured to produce products that satisfy the demand. The later iteration of the model covers ramp-up and safety buffers of capacity [38]. MIP (Mixed Integer Programming) is used to maximize the cash flow: (i) revenue: sales of products and salvage of systems (ii) capital expenses: investments in systems, (iii) operational expenses: reconfiguration costs, along with an opportunity cost of excess capacity and product shortages.

The model by Gyulai et. al. [39–41] was made in three iterations and has the purpose to evaluate the allocation of capacity investments among reconfigurable, dedicated, and flexible systems in uncertain contexts. The scope covers a factory of systems with modules for production of products to satisfy the demand. The second iteration [40] expands with outsourcing, shifts, multiple systems, and a rolling horizon heuristic to mimic uncertainty of demand. The third iteration [41] expands with modules to enable reconfigurations of systems, reconfiguration cost and time, inventory of products, and space requirements of systems. The model uses hierarchical planning and is decomposed to a (i) strategic component for long-term investment and allocation decisions, and a (ii) tactical component for mid-term capacity and production decisions. The latter is inter-dependent on the former, where feedback mechanisms are used to enable interaction and agreement. LP is applied to minimize the (i) capital expenses: investments of modules, and (ii) operational expenses: setup and reconfiguration cost of machines, labor cost of operators, holding cost of products, and an opportunity cost of late deliveries.

2.1.3. Models with a network scope

A model of *Local for Local* networks was proposed by Wörsdörfer et al. [42] which was later expanded in two iterations by Becker et al. [43,44] to account for demand uncertainty [43] and reconfigurability [44]. The purpose is to adapt the network by allocation of modules and demand to reduce time to market. The scope covers suppliers which deliver materials to factories, that can be opened or closed, with systems where its modules can be re-allocated in-between the distributed factories to gain vicinity to the demand of global locations. MIP is used to minimize (i) capital expenses: investment cost of factories and modules, (ii) operational expenses: transportation cost of modules, materials, and products; production cost of materials and products, and (iii) opportunity cost of demand shortages.

A model of reconfigurable *chain* networks was proposed by Guo et al. [45] which was expanded by Tian et al. [46] to account for outsourcing and disruptions. The scope covers suppliers that deliver materials to external factories which produce semi-finished products to internal factories that produce finished products to satisfy the demand. The purpose is to adapt the chain network by (re-)allocation of production steps across factories and reconfiguration of systems to reduce cost in multiple scenarios. MIP is used to minimize the operational expenses: procurement cost of materials, production and transportation cost of products of products, and reconfiguration cost of systems.

A preliminary model of reconfigurable systems in *web structure* networks was proposed by Kjeldgaard et. al. [47]. The scope covers factories with systems that can be reconfigured to produce, store, and transport components to regions with demand. The purpose is adaptation of the footprint to reduce total cost. IP (Integer Programming) is used to minimize capital expenses: investment in modules and operational expenses: reconfiguration cost of systems along with production, inventory, and transportation cost.

Most recently, a model of reconfigurable reversed *Hub and Spoke* networks was proposed by Epureanu et al. [11] to mitigate the scarcity of medical equipment imposed by the pandemic. The purpose is to adapt the network to an emergency situation where ventilators can be produced as well by reconfiguration of systems. The scope covers pre-established factories with systems for certain parts of a commercial product. LP is used to minimize the health risk which is approximated by unmet demand and lead-time of ventilators (ii) economic losses of commercial products.

2.2. Comparison of models and research gaps

This subsection provides a comparison of the reviewed models with respect to six categories: (i) the scope i.e. industrial environment, (ii) the approach i.e. methods and tools, (iii) the objectives i.e. performance measures, (iv) the variables i.e. decision mechanisms, (v) the limitations i.e. constraints and parameters, and (vi) the validation i.e. context and approach. At the end of the section, a summarized comparison is provided in Table 2, which reflect the research gaps and the extent of these.

2.2.1. Scope

Three models have been identified as having a system scope [33–36], two models have a factory scope [37–41], whereas the remaining four models have a network scope [11,42–47]. The models with a network scope are all dedicated to one of the phenotypes proposed by Meyer et al. [8]. Individually, they support a local for local network [42–44], a chain network [45,46], a web-structure network [47], and a reversed hub and spoke network [11]. However, neither support a mixed phenotype. Moreover, there is only limited support for the web-structure, as it is solely the preliminary model proposed by Kjeldgaard et al. [47] that considers this phenotype. This imposes issues for the evaluation of reconfigurability in the most common network phenotype i.e. web-structures [8], which is estimated to account for a share of ≥ 30% in industry [9] and is suggested as the phenotype of the future [2].

Table 2
Comparison of considerations and research gaps across state-of-the-art models for evaluation of reconfigurable production systems.

	System			*Factory*		*Network*			
Model	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Source	[33]	[34]	[35,36]	[37,38]	[39–41]	[42–44]	[45,46]	[47]	[11]
Scope									
Web structure network								✓	
Approach									
Monolithic evaluation	✓	✓	✓	✓		✓	✓	✓	
Uncertainty by scenarios		✓	✓	✓	✓	✓	✓		
Uncertainty by rolling horizon					✓	✓			
Objectives									
Minimize capital expenses	✓	(✓)		✓	✓	✓		✓	
Minimize operational expenses	✓	(✓)		✓	✓	✓	✓	✓	
Maximize sales revenue	✓			✓					
Variables									
Reconfigurations of systems	✓		✓		✓	✓		✓	✓
Production of products	✓	✓	✓	✓	✓	✓	✓	✓	✓
Production of system modules									
Inventory of products					✓			✓	✓
Inventory of system modules									
Transportation of products			(✓)			✓	✓	✓	
Transportation of system modules			(✓)			✓			✓
Limitations									
Ramp-up capacity of systems				✓					✓
Lifetime capacity of systems	(✓)			(✓)					
Spatial capacity of factories		✓			✓	✓			
Validation									
Validated in a real industrial case		✓			✓	✓	✓	✓	✓
Sufficient extent of horizon	✓	✓		✓	✓				
Sufficient granularity of horizon			✓		✓			✓	✓

2.2.2. Approach

One model solely applies simulation [34] and one model applies a combination of simulation and optimization in its second iteration [38] whereas the remaining seven models apply optimization. Three models use MIP as the engine of optimization [37,38,42–46], whereas four models use LP [11,33,35,36,39–41] and one model uses IP [47].

Two models [11,39–41] use hierarchical planning in the optimization which is decomposed to a tactical model for mid-term reconfiguration and production decisions, and a strategic model for long-term investments and allocations. Although this decomposition is beneficial for iterative planning, as it reduces complexity, it is disadvantageous for the less recursive evaluations, as it generates a risk of suboptimality [48]. In contrast, the counter i.e. monolithic approach that integrates decisions across the hierarchy, produces relatively better results [48].

Three models delimit uncertainty [11,33,47], whereas the remaining six include the consideration, although two of these only consider it in some iterations [39,42]. These six cover uncertainty by means of scenario application, either for parameters of the design which is related to the system evaluand, or for parameters of the context which is related to the evaluation environment. The design scenario parameters include the reconfiguration time [35,37], the ramp-up patterns [38], the module requirements [36], the production expenses [40], and the capital expenses [41]. The context scenario parameters include the service level [38], the transportation expenses [46], the transportation time [35], the supplier capabilities [45,46], the production cycle time [41], and the demand patterns of products which includes the lifecycle, volume, and mix [37,38,41]. Although aforementioned parameters can all be relevant to include in the evaluation due to context-specificity, the demand uncertainty is still stated to be the most critical to include when evaluating the investment of reconfigurable designs [4,17,18,21,34,49]. However, since eight models apply optimization as the approach, the demand scenarios are still deterministic and known with certainty without bounded rationality in each run. Although this imposes an issue, it is still rather common within the field of evaluation [24]. However, the issue is not the application of demand scenarios as is still proposed [10,24,49], but rather that it should be complimented with a rolling horizon heuristic for multiple time periods [10,24,32] which is used by two models in some of their iterations [40,41,43,44].

2.2.3. Objectives

The objective function of the models differs in terms of included aspects and the extent to which they are covered. They either focus on the minimization of capital expenses, the minimization of operational expenses, maximization of revenue, or a combination of aforementioned.

One model with a system scope [35,36] and two models with a network scope [11,45,46] delimit the investments and capital expenses of systems and modules. This limits the evaluation to capture the potential reduction of capital expenses [10,33] which can be enabled by reuse of modules that allows to extend the life and utility of the systems beyond their initial functionality [1,14,16,49–51].

Two models delimit operational expenses and instead focus on time [35,36] or throughput [11]. The remaining seven models that include operational expenses consider several aspects which depends on the scope and variables that are covered by the models. These aspects include, but are not limited to, the reconfiguration costs of systems [33,34,37,38,41,45–47], the production costs of products [33,34,38–47], the transportation cost of products [42–47], the transportation cost of system modules [42–44], the inventory cost of products [41,47], along with the opportunity costs of product shortages [37,38,43], excess capacity [37,38], or delivery lateness [41]. These aspects can all be relevant to include depending on the scope, where the network increases the extent to be covered. The delimitation hereof limits the evaluation in capturing the potential benefits of the designs on the related aspects.

Two models include revenue which covers the sales of products [33,37,38] and the salvage of systems [33,37,38]. The remaining seven models delimit revenue which limits the evaluation in capturing the potential increase of sales revenue through reduced time-to-market. Yet, three of these models partially cover benefits of reduced time-to-market by imposing an increase of opportunity costs of shortages [37,38,44] or late deliveries [41]. In contrast, the remaining models and early iterations of aforementioned include a no-backlog constraint to ensure the demand is satisfied in due time [11,34–36,39–41,43,45–47]. All four models with a network scope minimize cost with no backlogs with the exception of one iteration [44] and one model with partial consideration for some products [11]. This is presumably necessitated by the industrial cases due to the complexity of revenue structures for GPNs that are comprised of internal and external organizations [2].

2.2.4. Variables

Six models include variables for the reconfiguration of systems by exchange of modules [11,33,35,36,39–44,47]. The remaining three models delimit this consideration and instead treat reconfigurability as a generic property of the system [34,38] or factory [42,43,45,46]. This imposes an issue for the evaluation of design concepts in industrial cases as it inhibits the modelling of specific architectures of systems and requirements for modules [17,31,34].

All nine models include variables for the production of products at factories and the related production capacity. Yet, it is only two models with a system scope [33,34] and two models with a factory scope [37–41] that consider the expenses of excess production capacity with respect to unutilized labor during less active periods of production by incorporation of workforce mechanisms. However, this consideration is delimited from all four models with a network scope. This is presumably due to the complexity of GPNs, where a multitude of different mechanisms can be employed across the globally distributed factories [2].

All nine models delimit variables for the production of systems and modules at system suppliers and the related production capacity. Yet, it is proposed to account for the supply of systems and its modules [18] and the impact on the system suppliers' operations [19] as it can constrain the production capacity of products at the factories and create a risk of prolonging the time-to-market. Moreover, it is sensible to consider, as (i) systems and modules are products of system suppliers [1,52–54], and (ii) given the recent advances towards platform-based co-development between the product and production domain which is a prerequisite to design reconfigurable architectures [55].

Three models include variables for inventory of products [11,41,47] whereas the remaining six models delimit this consideration. This impose an issue for the evaluation as inventory can be a useful tactical mechanism to employ to hedge against fluctuations of demand. It can be relevant in slump periods to prepare for future peaks, as opposed to an increase of production capacity by means of additional system investments [48]. Moreover, slumps can be used to reconfigure systems to cater for demand changes without an increase of inventory or capacity which can be needed in the case of dedicated systems [47].

All nine models delimit variables for inventory of system modules. This impose issues for the evaluation [19,56,57]. This is reasoned as an inventory of modules can be used to negate the lead-time constraints for the module supply and the related risks of (i) order backlogs of products [58,59] or (ii) increased distance and costs of transportation [60]. The former risk relates to a necessity of awaiting modules required for the reconfiguration of systems to produce the products which satisfy the demand. The latter risk relates to the possibility of being unable to produce at the factory with vicinity to the demand, but instead at an alternative factory which potentially operates on another continent.

All five models with system or factory scope delimit the transportation of products [33–41], although one of these partially considers it [35,36] by handling of parts between cells [35,36]. In contrast, only one model with a network scope delimits it [11], whereas the remaining four includes it. These either include the transportation of products (i) from suppliers to factories with many-to-many relations [45,46], (ii) from factories to regions with one-to-one relations [42–44], or (iii) from factories to regions with many-to-many relations [47]. However, it is only the latter model that is applicable to evaluate the reconfigurability potential in network web-structures where the demand is allocated to be produced at, and delivered from, a set of glocal factories with varying transportation penalties. This potential has become critical due to recent change drivers [4]. These include: localization requirements [1,27,28], transport costs [27,28] and restrictions [1], shutdowns of factories and lines [1,3], and fluctuations of demand [1–3]. Specifically, the web structures with globally distributed factories can utilize reconfigurable production systems to increase the adaptability and resilience of the network, to mitigate these drivers [4], by enabling rapid and efficient changes of factories' production mix [27].

All five models with system or factory scope delimit the transportation of modules [33–41], although one of these partially considers it by handling of modules between cells [35,36]. Two models with a network scope delimits it [45–47], whereas the remaining two include transportation of modules between factories with many-to-many relations [11,42–44]. Yet, these models assume that a limited and fixed set of modules within the established network are sufficient to provide the needed functionality and capacity across factories. However, the transportation of modules from system suppliers to factories along with the lead-time and capacity constraints that can influence the supply is stressed to be accounted for [18,19], as it can influence the adaptability and resilience of the production network.

2.2.5. *Limitations*

Two models consider the impact of reconfigurations of systems on the time to ramp-up the production capacity [11,37,38]. Seven models delimit the consideration which limits the evaluation to capture the potential impact on production capacity where the reuse of already up-and-running systems can negate the ramp-up phase which in return increase the responsiveness of a factory or network [11,37,38]. When ramp-up is considered, an index of 50% with a linear trend for a fixed period is used [37,38].

All nine models delimit the lifetime capacity of systems and modules including utilization hereof upon production. Yet, it is suggested to be included [10,33], due to the impact it can impose on the number of investments, especially in capital-intensive industries [37]. Two models [33,37,38] partially considers it by means of depreciation and salvage of investments' value. However, it is not always possible to salvage the remaining value of investments at the end of the evaluation horizon when the systems and modules are proprietary and customized, that often requires in-house or strategic suppliers [19]. Therefore, lifetime capacity and utilization hereof are suggested to be explicitly included in the evaluation for systems at factories and suppliers alike.

Three models consider that systems occupy and utilize the finite spatial capacity that is available on the shop-floor of factories [34,39, 41–44]. The remaining six models delimit this consideration which impose an issue for the evaluation. This occurs as spatial capacity can constrain the scalability and number of systems that can be installed within a factory. In return, this can limit the localization of production in response to fluctuations in demand: where reconfigurability has been proposed to be used as a mitigation tactic [18,27,28]. This limitation is especially present in large-scale or capital-intensive contexts [28,37].

2.2.6. *Validation*

Three models are not validated in real industrial cases [33,35–38] whereas the remaining six are in either of the following industries. The mechatronic industry [34], the capital goods industry [34,47], the chemical industry [42–44], the electronics industry [45,46], and the automotive industry [11,39–41]. However, only two of these evaluate an actual industrial design [34,47], whereas the remaining five only consider the industrial context [11,39–46]. This indicates a gap between academia and industry, which is a general issue in the field [10,20] that limits the industrial transition [10]. In order to further advance the transition, models and examples which support the evaluation of actual industrial designs are needed [10,17,20]. Moreover, the relevance of reconfigurability for the network level is indicated, since it is the scope of four out of the six models with industrial validations [11,42–46]. This conforms with the proposition to expand the research of reconfigurability of the production network [4,26], as the lack hereof is a main challenge in the industrial transition [30].

The evaluation horizon of the models differs in terms of granularity and extent with respect to the case validation. Five models with a system or factory scope decompose the horizon with a granularity of years and an extent of either 8 [33], 9 [37], or 10 time periods [34,38,41]. Depending on their iteration, the remaining models with this scope either decompose to (i) quarters of 30 [39] or 16 periods [40] or (ii) days of 840 periods [35] or 4-hour shifts of 24 periods [36]. Two models with a network scope neither specifies the granularity nor the extent of the horizon [42–46]. The remaining two models with this scope either decompose to months of 8 periods [11] or weeks of 52 periods [47]. This pattern suggests that the increased complexity of the network scope limits the granularity and the extent of the horizon which imposes an issue for the evaluation [4,18]. It occurs as reconfigurable designs of production systems have an increased investment, compared to dedicated counterparts, although they are less expensive when changes occur as they can extend the lifetime and utility of systems across product generations [1,14,16,49–51]. This thereby aids to cancel out the increased initial investment over time [49,51], where the production systems have a longer lifetime than the lifecycle of the related products [14,20]. Therefore, the evaluation horizon is suggested to be five years and preferably ten years or longer in order to be sufficient [49]. Similarly, the granularity is suggested to be on quarterly level and preferably on a monthly level or lower in order to be sufficient [41]. These levels enables to model the tactical mechanisms of reconfigurability and to capture the potentials hereof in the evaluation [41]. Although, it should be noted that the suitable extent of granularity is more case-dependent than the horizon.

2.2.7. *Research gaps*

The research gaps, and the extent hereof is indicated in the comparison across models in Table 2. The first column lists the 20 considerations, in the 6 categories, that are deemed necessary to include in the evaluation model by extant literature as discussed in Subsection 2.2. The subsequent columns provides checkmarks if the models include the considerations, parenthesized checkmarks if the models partially include the considerations, and blank cells if the models delimit the considerations. The delimitations and the number of models with the delimitations indicates the research gaps and the extent hereof. A summation and a classification of the delimitations is provided in Section 7.

Based on the outlined research gaps, there is a need for a monolithic optimization model with objective to minimize cost of a global production network with a web structure to meet uncertain demands, by using a set of scenarios and rolling horizon heuristics, that considers: (i) exchange of modules enable reconfigurations of systems, (ii) capital investments and the related lifetime utilization of systems and modules at factories and suppliers (iii) production of systems, modules, and products at factories and suppliers, (iv) reconfigurations of systems impact ramp-up time and hereby production capacity of products, (v) inventory of modules and products at factories and suppliers, (vi) transportation of modules from suppliers to factories and transportation of products from factories to regions.

3. Proposed model

The proposed model applies mathematical optimization, using integer programming, to evaluate the performance impact, with respect to capital and operational expenses, of reconfigurable designs of production systems within a global production network of chained web structures. The model is represented using the IDEF0 method in Fig. 1.

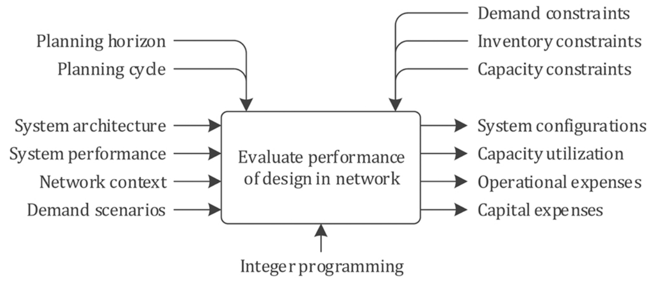

Fig. 1. IDEF0 representation of proposed optimization model.

The modeled production network is illustrated in Fig. 2. It is composed of two sets of dyadic relationships with unidirectional flow. The network contains an outbound flow of products from factories to regions and an inbound flow of production system modules from suppliers to factories. The network is thereby triadic, as it covers three interlinked vertical tiers of entities. Further, the network is multi-domain, as it covers both production and logistic operations with respect to two types of units.

The model is composed of (i) constituents: decision variables, calculated variables, input parameters, output parameters, and objectives; and (ii) interrelations: variable calculations and constraints.

The primary constituents and interrelations are illustrated in Fig. 3 with a vertical structure according to the flow of units through operations across entities in the network where (i) units refer to systems, modules, and products, (ii) entities refer to suppliers, factories, and regions, and (iii) operations refer to activities of production, inventory, reconfiguration, and transportation of units. Notations and descriptions of constituents are provided in Table 3 with similar sequence as in Fig. 3, yet in separate categories. The notations are constructed with reference to (i) the operation (ii) the unit, and (iii) an optional area e.g., time.

Throughout Sections 3.1 to 3.3, the main constituents and interrelations are formulated as mathematical equations. The output parameters, which are delimited from Fig. 3, are instead provided in Appendix A. In contrast to the main constituents, the output parameters do not influence the results of model runs for evaluation, but rather provide explanatory operational insights of the economic results.

Delimitations are indicated throughout the formulations, which are discussed in terms of implications and modifications to resolve these in Section 7. However, it is important to note that the model is constructed with a one-to-one mapping between variants of system configurations and variants of products in terms of functionality for their production. The aforementioned carries implications for how dedicated, flexible, and reconfigurable designs of production systems should be formulated in terms of architecture inputs, which is discussed in Section 7.

Indice v refers to interlinked (i) variants of products and (ii) configuration states of production systems. A special notation of $\widetilde{v}$ is applied in conjunction with v where $\widetilde{v} \neq v$ for model constituents related to the reconfiguration of production systems between certain states, where the former refers to the subsequent configuration state and the latter refers to the prior configuration state.

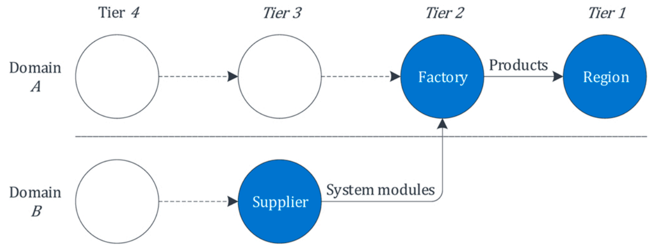

Fig. 2. Entities, units, and interrelations within the network.

3.1. Economic objectives

The objective in Eq. (1) is to minimize tcost with respect to the decision variables, subject to the constraints and variable calculations, given specified values for inputs.

$$Minimize(\text{tcost}) \tag{1}$$

In Eq. (2), tcost is calculated by a summation of tcapex and topex composed of respective sub-objectives. Calculations for sub-objectives are provided throughout Eqs. (5–11) which are formulated as sum-products of values from (i) a related decision- or calculated variable and (ii) a specified input value, across respective indices.

$$\text{tcost} = \text{tcapex} + \text{topex} \tag{2}$$

In Eq. (3), tcapex is calculated by summation of tpes and tpem covering the total capital expenses in terms of investments in the production of systems and modules. In Eqs. (4–5), the former refers to systems utilized by suppliers to produce modules, and the latter refers to modules of systems used by factories to produce products.

$$\text{tcapex} = \text{tpes} + \text{tpem} \tag{3}$$

$$\text{tpes} = \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{m=1}^{M}\text{ps}_{mst} * \text{pes}_{ms} \tag{4}$$

$$\text{tpem} = \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{m=1}^{M}\text{pm}_{mst} * \text{pem}_{ms} \tag{5}$$

In Eq. (6) topex is calculated by summation of ttem, tres, tpep, tiep, and ttep, which covers the total operating expenses of transported modules, reconfigured systems along with produced, stored, and transported products.

$$\text{topex} = \text{ttem} + \text{tres} + \text{tpep} + \text{tiep} + \text{ttep} \tag{6}$$

In Eqs. (7–8) ttem and ttep represent the total cost of units transported from up- to downstream entities. The former for modules from suppliers to factories, the latter for products from factories to regions. Bidirectional flows of units between entities in horizontal tiers e.g. modules between factories is delimited, yet discussed in Section 7.

$$\text{ttem} = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{s=1}^{S}\sum_{m=1}^{M}\text{tm}_{msft} * \text{tem}_{msft} \tag{7}$$

$$\text{ttep} = \sum_{t=1}^{T}\sum_{r=1}^{R}\sum_{f=1}^{F}\sum_{v=1}^{V}\text{tp}_{vfrt} * \text{tep}_{vfr} \tag{8}$$

In Eq. (9) calculations are provided for tres, which represents the total labor- and rental costs of resources to (dis-)assemble modules during system reconfigurations.

$$\text{tres} = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{\widetilde{v}=0:\widetilde{v}\neq v}^{V}\sum_{v=0}^{V}\text{rs}_{\widetilde{v}vft} * \text{res}_{\widetilde{v}vf} \tag{9}$$

In Eq. (10) tpep is calculated, which cover the total material- and labor costs of produced products. A holding cost index times pep can be used for iep to calculate tiep in Eq. (11) covering total inventory costs of products.

$$\text{tpep} = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{v=1}^{V}\text{pp}_{vft} * \text{pep}_{vf} \tag{10}$$

$$\text{tiep} = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{v=1}^{V}\text{iap}_{vft} * \text{iep}_{vf} \tag{11}$$

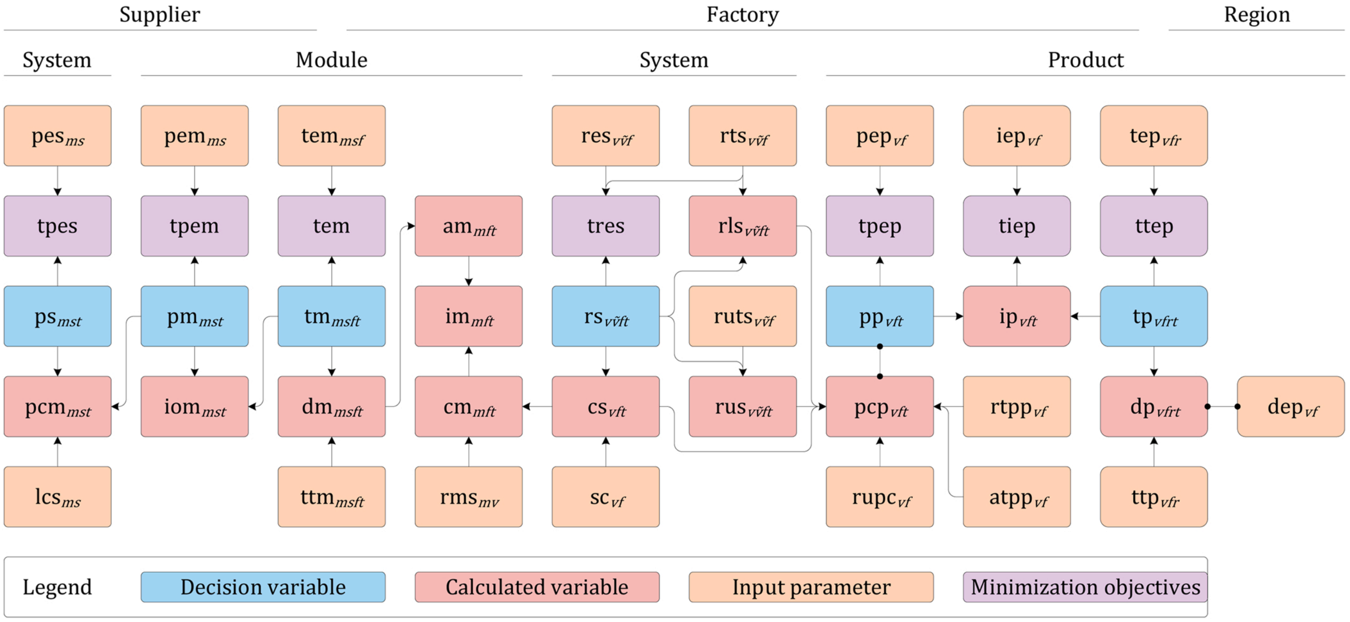

Fig. 3. Vertical classification of the primary constituents and interrelations in the proposed optimization model.

3.2. Constraints

Eqs. (12–17) constrain decision variables to take integer values: enabling applicability in discrete contexts.

$$\mathrm{ps}_{mst} = INT, t > 0 \tag{12}$$

$$\mathrm{pm}_{mst} = INT, t > 0 \tag{13}$$

$$\mathrm{tm}_{msft} = INT, t > 0 \tag{14}$$

Indice $v = 0$ is excluded from the constraints provided in Eqs. (12–24) with exception for Eqs. (15–21) to enable reconfigurations of systems from empty states.

$$\mathrm{rs}_{\tilde{v}vft} = INT, \tilde{v} \neq v, t > 0 \tag{15}$$

$$\mathrm{pp}_{vft} = INT, v, t > 0 \tag{16}$$

$$\mathrm{tp}_{vfrt} = INT, v, t > 0 \tag{17}$$

Eqs. (18–23) constrain a set of calculated variables to be non-negative: capacity, configuration, and inventory.

$$\mathrm{pcm}_{mst} \geq 0, t > 0 \tag{18}$$

$$\mathrm{iom}_{mst} \geq 0, t > 0 \tag{19}$$

$$\mathrm{im}_{mft} \geq 0, t > 0 \tag{20}$$

$$\mathrm{cs}_{vft} \geq 0, t > 0 \tag{21}$$

$$\mathrm{ip}_{vft} \geq 0, v, t > 0 \tag{22}$$

Eq. (23) constrains production to be less than or equal to available capacity: which drives reconfigurations and the required upstream capital investments.

$$pp_{vft} \leq pcp_{vft}, v, t > 0 \tag{23}$$

Eq. (24) constrains demand to be equal to products delivered which delimits possibility for backlog of orders. The impact and mitigation hereof is discussed in Section 7.

$$\sum_{f=1}^{F} \mathrm{dp}_{vfrt} = \mathrm{dep}_{vrt}, v, t > 0 \tag{24}$$

3.3. Variable calculations

Throughout Eqs. (25–33) and (38) variables are limited to $v > 0$ whereas $v \geq 0$ is covered by variables directly related to reconfigurations in Eqs. (34–37).

In Eq. (25) pcm is calculated as a function of ps times lcs subtracted with pm and added with pcm in $t - 1$. It represents a production capacity that can be stored similar to inventory, and it is generated by a set of system modules with a specified lifetime in units, that is utilized upon the demand for pm. The impact of material and labor availability on pcm is delimited, yet discussed in Section 7.

$$\mathrm{pcm}_{mst} = \mathrm{pcm}_{ms(t-1)} + \mathrm{ps}_{mst} * \mathrm{lcs}_{ms} - \mathrm{pm}_{mst}, t > 0 \tag{25}$$

In Eq. (26) dm is calculated as a function of tm in $t - \mathrm{ttm}$. Similar is applied for dp in Eq. (27). Delivery thereby represent end of transport and receipt of demand.

$$\mathrm{dm}_{msft} = \mathrm{tm}_{msf\left(t-\mathrm{ttm}_{msf}\right)}, t > 0 \tag{26}$$

$$\mathrm{dp}_{vfrt} = \mathrm{tp}_{vfr\left(t-\mathrm{ttp}_{vfr}\right)}, v, t > 0 \tag{27}$$

In Eq. (28) iom is calculated as pm subtracted with tm added with iom from $t - 1$. Similar is applied for ip in Eq. (29). In/out-bound inventories represent units at the end of each period which contrast to Eq. (30) where iap is calculated as average between t and $t - 1$.

$$\mathrm{iom}_{mst} = \mathrm{iom}_{ms(t-1)} + \mathrm{pm}_{mst} - \sum_{f=1}^{F} \mathrm{tm}_{msft}, t > 0 \tag{28}$$

$$\mathrm{ip}_{vft} = \mathrm{ip}_{vf\mathrm{t}} + \mathrm{pp}_{vft} - \sum\nolimits_{r=1}^{R} \mathrm{tp}_{vfrt}, v, t > 0 \tag{29}$$

$$\mathrm{iap}_{vft} = \left(\mathrm{ip}_{vf(t-1)} + \mathrm{ip}_{vft}\right)/2, v, t > 0 \tag{30}$$

In Eq. (31) im is calculated as am subtracted with cm. However, im does not directly accumulate over time as iom and ip, but indirectly through am in Eq. (32) calculated as dm added with am from $t-1$. Thereby, am covers modules: delivered, on inventory, and configured.

Table 3
Notation and description of model constituents.

Notation	Description
Indices	
t	$t \in [0, T], T \in \mathbb{N}$ Discrete time periods within evaluation horizon
v	$v \in [0, V], V \in \mathbb{N}$ Variants of production systems and products
m	$m \in (0, M], M \in \mathbb{N}$ Modules, i.e. building blocks, of system variants
s	$s \in (0, S], S \in \mathbb{N}$ Suppliers, i.e. vendors, of system modules
f	$f \in (0, F], F \in \mathbb{N}$ Factories i.e. manufacturers of products
r	$r \in (0, R], R \in \mathbb{N}$ Regions i.e. receivers of products
Decision variables	
ps_{mst}	Production of systems for m at s in t
pm_{mst}	Production of modules m at s in t
tm_{msft}	Transportation of modules m from s to f in t
$\mathrm{rs}_{v\widetilde{v}ft}$	Reconfiguration from systems v to $\widetilde{v}$ at f in t
pp_{vft}	Production of products v at f in t
tp_{vfrt}	Transportation of products v from f to r in t
Calculated variables	
pcm_{mst}	Production capacity for modules m at s in t
iom_{mst}	Outbound inventory of modules m at s in t
dm_{msft}	Delivery of modules m from s to f in t
am_{mft}	Available modules m at f in t
im_{mft}	Inventory of modules m at f in t
cm_{mft}	Configured modules m at f in t
cs_{vft}	Configured systems v at f in t
$\mathrm{rls}_{v\widetilde{v}ft}$	Reconfiguration load from systems v to $\widetilde{v}$ at f in t
$\mathrm{rus}_{v\widetilde{v}ft}$	Ramp-up from systems v to $\widetilde{v}$ at f in t
pcp_{vft}	Production capacity for products v at f in t
ip_{vft}	Inventory of products v at f in t
iap_{vft}	Average inventory of products v at f between t
dp_{vfrt}	Delivery of products v from f to r in t
Input parameters	
pes_{ms}	Production cost of system for m at s
lcs_{ms}	Lifetime capacity of system for m at s
pem_{ms}	Production cost of module m at s
lcm_{ms}	Lifetime capacity of module m from s
tem_{msf}	Transport cost of module m from s to f
ttm_{msf}	Transport time of module m from s to f
rms_{mv}	Required module m for system v
$\mathrm{res}_{v\widetilde{v}f}$	Reconfiguration cost from system v to $\widetilde{v}$ at f
sc_{f}	Spatial capacity for systems at f
$\mathrm{rts}_{v\widetilde{v}f}$	Reconfiguration time from system v to $\widetilde{v}$ at f
$\mathrm{res}_{v\widetilde{v}f}$	Reconfiguration cost from system v to $\widetilde{v}$ at f
$\mathrm{ruts}_{v\widetilde{v}f}$	Ramp-up time from system v to $\widetilde{v}$ at f
rupc	Ramp-up production capacity index
atpp_{vf}	Available time for production of product v at f
rtpp_{vf}	Required time for production of product v at f
pep_{vf}	Production cost of product v at f
iep_{vf}	Inventory cost of product v at f
tep_{vfr}	Transport cost of product v from f to r
ttp_{vfr}	Transport time of product v from f to r
ldp_{fr}	Local delivery index of products from f to r
dep_{vrt}	Demand of product v at r in t
Output parameters	
tps	Total produced systems at supplier
tulcs	Total utilization of lifetime capacity of systems
tdm	Total deliveries of system modules
tds	Total deliveries of complete systems
tdvm	Total deliveries of varying system modules
tim	Total inventory of system modules
tif	Total installations of factories
tusc	Total utilization of spatial capacity at factories
tafr	Total average functionality range of factories
tirs	Total initial reconfigurations of systems
tsrs	Total subsequent reconfigurations of systems
trsi	Total reconfigurations of systems from inventory
tpcp	Total production capacity for products
tupcp	Total utilization of production capacity for products
tulcm	Total utilization of lifetime capacity of system modules
taip	Total average inventory of products
tldp	Total local deliveries of products
Economic objectives	
tpes	Total production cost of systems
tpem	Total production cost of modules
ttem	Total transport cost of modules
tres	Total reconfiguration cost of systems
tpep	Total production cost of products
tiep	Total inventory cost of products
ttep	Total transport cost of products
tcapex	Total capital expenses
topex	Total operational expenses
tcost	Total cost
Run parameters	
pw	Discrete time periods within planning window
pc	Discrete time periods between planning cycles

The difference arises due to cm in Eq. (33), a function of cs times specified rms, which represents a continuous utilization and demand of system modules, which contrast to dep i.e., the comparative episodic demand of products.

$$\mathrm{im}_{mft} = \mathrm{am}_{mft} - \mathrm{cm}_{mft}, t > 0 \tag{31}$$

$$\mathrm{am}_{mft} = \mathrm{am}_{mf(t-1)} + \sum_{s=1}^{S} \mathrm{dm}_{msft}, t > 0 \tag{32}$$

$$\mathrm{cm}_{mft} = \mathrm{cs}_{vft} * \mathrm{rms}_{vm}, t > 0 \tag{33}$$

In Eq. (34) cs is calculated as cs in $t-1$ subtracted with rs for v and added with rs for $\widetilde{v}$. Hereby, cs represents a set of system configurations which can be reconfigured from one set of states to another, although an initial set is required. The latter is represented in Eq. (35) where cs for v, $t = 0$ is dependent on specified scs, representing the spatial capacity for systems at factories. It is possible to input a set of already configured systems covered by the design’s functionality range, that is discussed in Section 7.

$$\mathrm{cs}_{vft} = \mathrm{cs}_{vf(t-1)} - \mathrm{rs}_{vft} + \mathrm{rs}_{\widetilde{v}ft}, t > 0 \tag{34}$$

$$\mathrm{cs}_{vft} = \mathrm{sc}_{f}, v, t = 0 \tag{35}$$

In Eq. (36) rls is calculated as a function of rs times specified rts, representing the required reconfiguration time. In Eq. (37) rus is calculated as a function of rs in consecutive previous periods back in time as specified by ruts, representing the consecutive ramp-up state of systems. The logic of rls is a time impact which is subtracted from the available production capacity within a certain period, whereas rus it is a percentage loss impact which limits production capacity across multiple periods.

$$\mathrm{rls}_{v\widetilde{v}ft} = \mathrm{rs}_{v\widetilde{v}ft} * \mathrm{rts}_{v\widetilde{v}f}, t > 0 \tag{36}$$

$$\mathrm{rus}_{v\widetilde{v}ft} = \sum\nolimits_{i=0}^{ruts_{v\widetilde{v}f}} rs_{v\widetilde{v}f(t-i)}, t > 0 \tag{37}$$

In Eq. (38) pcp is calculated as a subtraction of cs with rus for $\widetilde{v}$ times rupc, then timed with a subtraction of atpp with rls for $\widetilde{v}$ divided by rtpp. The first component represents a configuration state of systems, which can be in a state of ramp-up with a specified loss of production capacity with respect to the nominal. The former act as determinant for functionality, and thus capacity, whereas the latter act as limit on capacity. The second component represents a specified available production time, loaded with the required reconfiguration time, then divided by the specified required production time. The input atpp is proposed to be specified by number of shifts, hours/shift and shifts/month, whereas rtpp can be specified by the cycle- or takt time of producing the product on the system. Both rus and rls are summated over v to acquire $\tilde{v}$ as it represents the state going to, which thus match with v in the interconnected constituents cs and rtpp respectively. Meaning, it is the configuration state that determines the capacity for production of specific product variants.

$$\mathrm{pcp}_{vft} = \left(\mathrm{cs}_{vft} - \sum_{v=1}^{V} \mathrm{rus}_{\tilde{v}vft} * \mathrm{rupc}\right) * \left(\frac{\mathrm{atpp}_{vf} - \sum_{v=1}^{V} \mathrm{rls}_{\tilde{v}vft}}{\mathrm{rtpp}_{vf}}\right), v, t > 0 \qquad (38)$$

4. Method for model application

The method proposed to apply the model is illustrated in Fig. 4. It consists of six activities related to (i) data collection and (ii) data analysis with respect to the results.

With regards to the former, input values are required to be collected, specified, and categorized as being dependent on the design, context, or scenario. There is a degree of freedom for the categorization depending on the case. Nevertheless, from the literature review in Section 2, it is evident that some inputs are design-dependent no matter what. These include the system (i) architecture i.e., rms_{mv}, (ii) performance i.e. $\mathrm{rts}_{\tilde{v}vf}$, $\mathrm{res}_{\tilde{v}vf}$, and (iii) cost i.e. pm_{mst}. In contrast, $\mathrm{ruts}_{\tilde{v}vf}$, lcm_{ms}, and pep_{vf} can be influenced by the design. The distinction between context and scenario inputs is not as apparent, since the uncertainty desired to be considered depends on the case. However, the inputs of demand i.e., dep_{vrt} and t should be scenario-dependent, where historical data for legacy-, and forecasted for new-, product families are proposed to be used as inputs. Moreover, inputs related to the shop-floor and network conditions e.g. sc_f and tep_{vfr} have in recent times changed due to disruptions created by the pandemic, making them uncertain and relevant for scenarios.

Regarding the data analysis, the model is first configured and run with inputs for each design concept and scenario combination, where the context-dependent inputs remain static. Subsequently, the comparative performance of the reconfigurable, relative to dedicated and/or flexible, design concept(s) is calculated for each scenario with respect to the economic objectives and output parameters specified in Table 3. In this regard, relative performance is calculated by means of a delta-analysis on numerical and percentual difference. Finally, the average yearly relative performance across scenarios for all outputs is calculated, where an average generates an aggregate performance across scenarios, which is modified to a yearly average as the scenarios can differ on evaluation horizon T. Finally, the performance is presented to and evaluated by the managerial stakeholders at the designated gate within the development project. The evaluation has three outcomes (i) a transition to the detailed design with a pure-technical and/or socio-technical evaluation or (ii) a reiteration of the conceptual design regarding the architecture i.e., modularity and integrability and/or the functional design i.e. convertibility (iii) a reiteration on input collection, specification, or categorization, if the case has changed.

A rolling horizon heuristic is proposed to be applied for the optimization as illustrated in Fig. 5. It decomposes the problem into a set of cycles with windows for decision making, where the subsequent depends on the former. The complete evaluation horizon T is divided according to the planning window pw which is rolled across time periods t, throughout the horizon, according to the planning cycle pc.

The heuristic was proposed and tested by Baker [62] in the domain of production scheduling for multi-period finite-horizon optimization models. The utility is argued by the principal rationale that practice is bound by limited and uncertain information about the future [62,63]. The rationale, and thereby the heuristic, is also relevant for the design evaluation of reconfigurable production systems. The relevance is attributed to their capability to respond to uncertainty which is critical to account for in order to capture the long-term benefits of the investment [34,49]. Herein, the heuristic constructs uncertainty by limiting the availability and validity of the future demand information. This creates bounded rationality in the decision making where the implications of inferior decisions can compound throughout the horizon, which depends on the employed extent of reconfigurability enabled by the designs.

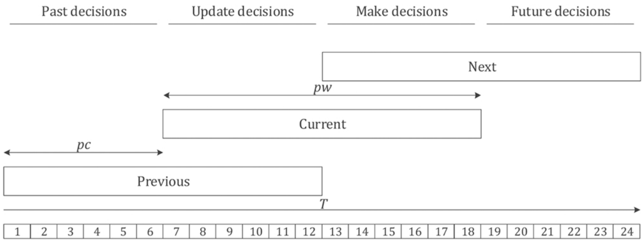

Fig. 5. Illustration of the rolling horizon heuristic proposed for the optimization runs.
Adapted from Scala et al. [61].

In principle, using information of the complete horizon in the optimization would generate increased performance [62]. Yet, this is not the case in industry where companies can rarely, if ever, accurately foresee the lifetime demand of a product family, where a mix of firm- and potential orders and forecasts is input for the tactical decisions.

5. Data collection

5.1. Case description

To demonstrate application of the model, it is applied to a case for a global enterprise in the capital goods industry. The case company is engaged in the development of a reconfigurable design of production systems for a new family of 4 components. This reconfigurable design is subject to the evaluation and compared to a dedicated design. Components are $\sim 10^2$ meters, where systems are $\sim 10^3$ square meters with a weight of $\sim 10^2$ tons. This scale contributes to long reconfiguration times of several weeks with large capital expenses of several million euros. The production network consists of system suppliers and ≥ 10 component factories that are dispersed globally for several regional markets. A factory employs a single double-digit number of systems, which amounts to ≥ 100 in total, with a lifetime of $\sim 10^4$ components. Thus, the scalability of factories and the required volume of systems is high.

Due to the components' size, it is efficient from a logistics perspective to fulfill demand from a factory with closest vicinity to the market. In contrast, due to the systems' size, reconfiguration time, and capital expenses, it is efficient from a investments perspective to dedicate factories to a production mix, which limits their supply capability. Thereby, trade-offs are present when demand fluctuations occur in terms of

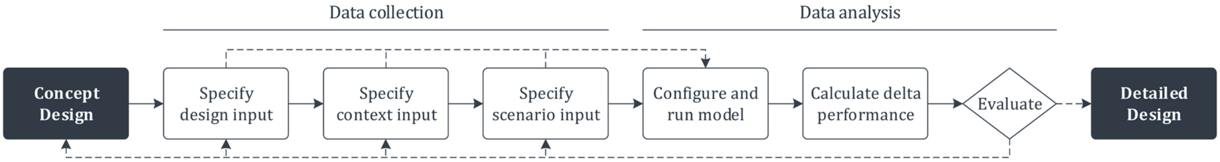

Fig. 4. Flow of activities to apply the proposed model for comparative performance evaluation of system designs.

timing, variety, volume, and location.

The reconfigurable systems are expected to mitigate the tradeoff by reducing the time and capital expenses of reconfigurations in half. Thereby the company expects to increase vicinity of production to demand, for a reduction of transport cost, without incurrence of the time and cost impact on systems upon required changes. However, the extent to which the trade-off is mitigated is uncertain, which is why an evaluation is desired considering the economic and operational performance of the new design before the detailed design and commissioning phase.

In addition to products and components, the company also produce the related production systems and modules. The company is thereby vertically integrated across tiers and domains of the network. Therefore, the impact on the system suppliers' operations and the imposed constraints to supply modules to glocal factories for reconfigurations is also desired to be evaluated. The design is thought to increase the lifetime utilization of modules, that impose a comparably decreased load on the supplier's production capacity and the capital expenses to achieve it. Moreover, due to systems' size and weight which impact transport cost and time: especially with high-volume requirements of modules, it is desired to include their transportation as well, especially as the volume is thought to decrease.

5.2. Input collection

The input data from the case are summarized in Table 4.

Due to confidentiality, only excerpts are provided i.e., as either static or minimum and maximum values across respective indices. Although, for certain inputs, values are (i) replaced with reference to a Table with granular data e.g., for the system architecture or (ii) is not available due to confidentially i.e., for the demand. Moreover, values are marked in terms of the design d and scenario(s) n, where the notation of baseline refers to a common input. The design concepts are denoted as $d = 1$ for the dedicated and $d = 2$ for the reconfigurable.

Both primary and secondary data have been collected through iterative field and desk research. The former refers to semi-structured interviews with employees of certain functional roles i.e., technical designer, technical lead, program manager, and/or supply chain (SC) planner. The latter refers to the data retrieved e.g., estimations,

Table 4

Summary of collected input data: static or min-max values, type of application, and the empirical sources with details.

Input	Value	Application	Data source (s)	
ws	12 months	Baseline	One-year planning horizon due to uncertainty from interviews with SC planner.	P
ss	6 months	Baseline	Semi-annual frequency of footprint planning from interviews with SC planner.	P
T	132 months	$n \leq 2$	10 years of historical demand of $c \leq 4$ [10-12] from the ERP system.	S
	72 months	$n \geq 3$	5 years of forecasted demand for $c = 7$ [10-12] from technical lead.	S
M	16 modules	Baseline	Specification for $c = 7$ from interviews with technical- lead and designers.	P
V	4(+1) variants	Baseline	Specification for $c = 7$ from interviews with technical- lead and designers.	P
S	1 supplier	Baseline	Delimitation of external suppliers from interviews with program manager.	P
F	7 factories	Baseline	Aggregation of factories to countries from interviews with technical lead.	P
R	4 regions	Baseline	Aggregation of regions to continents from interviews with program manager.	P
pes_{ms}	$85 \leftrightarrow 570$ k€	Baseline	Quotations for $c = 6$ at $s = dk$ *%$m2\Delta$ relative to $c = 7$ from technical lead.	S
lcs_{ms}	10 units	Baseline	Specification for $c = 7$ from interviews with technical- lead and designers.	P
pem_{ms}	$220 \leftrightarrow 835$ k€	$d = 1$	Quotations for $c = 6$ at $s = dk$ *%$m2\Delta$ relative to $c = 7$ from technical lead.	S
	$190 \leftrightarrow 665$ k€	$d = 2$	Projected material and labor cost for $c = 7$ from technical- lead and designers.	S
lcm_{m}	1500 units	Baseline	Specification for $c = 7$ from interviews with technical- lead and designers.	P
tem_{msf}	$15 \leftrightarrow 425$ k€	Baseline	Quotations for $c = 6$ from vendor *%$m2\Delta$ relative to $c = 7$ from technical lead.	S
ttm_{msf}	$1 \leftrightarrow 3$ months	Baseline	Monthly average of historical times for $c = 4, 5, 6$ [16-20] from the ERP system.	S
rms_{mv}	Table 5: left	$d = 1$	Dedicated design from interviews with technical lead and designers.	P
	Table 5: right	$d = 2$	Reconfigurable design from interviews with technical lead and designers.	P
sc_{f}	$4 \leftrightarrow 24$ lines	Baseline	Max configurations from global footprint [19-20] from SC manager.	S
	$2 \leftrightarrow 12$ lines	$n \leq 4$	Baseline * estimate of 50% for $c = 7$ from interviews with technical lead.	P
	$1 \leftrightarrow 6$ lines	$n = 5$	Baseline * estimate of 25% for $c = 7$ from interviews with program manager.	P
$\mathrm{rcos}_{v\tilde{v}f}$	$4\ \text{k€} * \mathrm{rts}_{v\tilde{v}f}$	Baseline	Quotation for $c = 4$ at $f = de$ [18] covering labor cost from program manager.	S
$\mathrm{rts}_{v=0,\tilde{v}\geq 1,f}$	21 days	Baseline	Time of installation from study on $c = 5, 6$ at $f = tr$ [20] from technical lead.	S
$\mathrm{rts}_{v\geq 1,\tilde{v}\geq 1,f}$	28 days	$d = 1$	Time of changeover from study on $c = 5, 6$ at $f = tr$ [20] from technical lead.	S
	14 days	$d = 2$	Estimated reconfiguration time for $c = 7$ from interviews with technical lead.	P
$\mathrm{rts}_{v\geq 1,\tilde{v}=0}$	7 days	Baseline	Time of dismantling from study on $c = 5, 6$ at $f = tr$ [20] from technical lead.	S
$\mathrm{rcos}_{v\tilde{v}f}$	$4\ \text{k€} * \mathrm{rts}_{v\tilde{v}f}$	Baseline	Quotation for $c = 4$ at $f = de$ [18] covering labor cost from program manager.	S
$\mathrm{ruts}_{v=0,\tilde{v}\geq 1,f}$	6 months	Baseline	Time of ramp-up from study on $c = 4, 5$ at $f = tr, de$ [19-20] from SC manager.	S
$\mathrm{ruts}_{v\geq 1,\tilde{v}\geq 1,f}$	6 months	$d = 1$	Time of ramp-up from study on $c = 4, 5$ at $f = tr, de$ [19-20] from SC manager.	S
	2 months	$d = 2$	Estimate of time of ramp-up for $c = 7$ from interviews with program manager.	P
rupc	50%	Baseline	lost capacity of ramp-up relative to nominal from interviews with SC planner.	P
atpp_{vf}	720 hours	Baseline	Nominal policy of 8 h * 3 shifts * 30 days from interviews with SC planner.	P
rtpp_{vf}	24 hours	Baseline	Nominal cycle time from interviews with technical lead and SC planner.	P
pep_{vf}	$235 \leftrightarrow 330$ k€	Baseline	Historical labor cost for $c = 4, 5, 6$ [16-20] from the ERP system *%$m\Delta$ relative to $c = 7$ + projected material cost for $c = 7$ from technical lead.	S
iep_{vf}	$2 \leftrightarrow 3$ k€	Baseline	Nominal policy of 10% production cost / 12 months from technical lead.	P
tep_{vfr}	$35 \leftrightarrow 215$ k€	$n \leq 3$	Regional average of historical transport costs for $c = 4, 5, 6$[16-20] from the ERP system x%$m\Delta$ relative to $c = 7$ from technical lead.	S
	$70 \leftrightarrow 430$ k€	$n \geq 4$	Baseline * estimate of 100% increase [21] from interviews with SC planner.	P
ttp_{vfr}	$1 \leftrightarrow 3$ months	Baseline	Average of historical transport times of $c = 4, 5, 6$ [16-20] from the ERP system.	S
ldp_{fr}	Table 6	Baseline	Estimation from interviews with SC manager based on geographical vicinity.	P
dp_{vrt}	Table 7	$n = 1$	Regional sum of historical demand of $c = 1$ [10-20] from the ERP system.	S
	Table 7	$n = 2$	Regional sum of historical demand of $c = 2, 3, 4$ [10-20] from the ERP system.	S
	Table 7	$n \geq 3$	Five-years of forecasted demand for $c = 7$ [22-26] from technical lead.	S

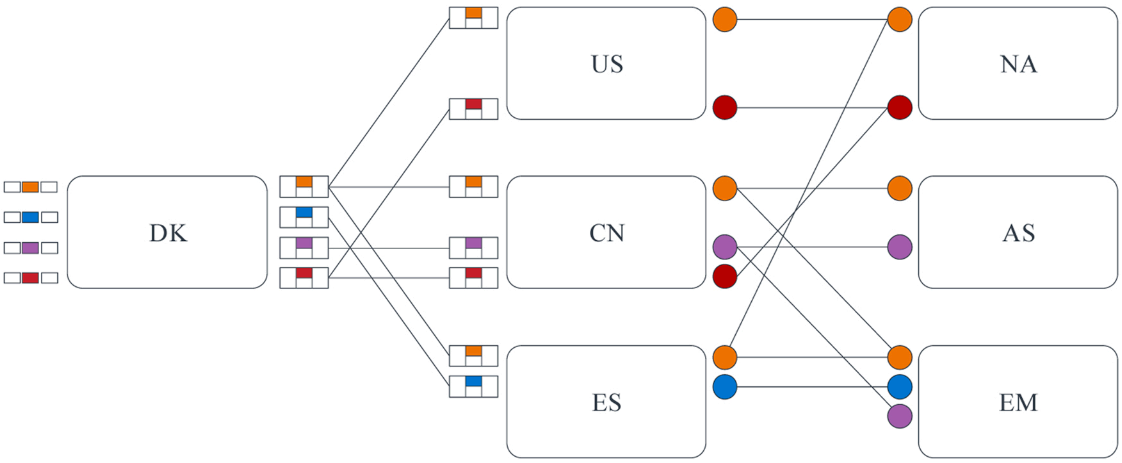

Fig. 6. Exemplification of case-indices and their interrelations.

specifications, or quotations along with delimitations and aggregations from various databases in the ERP system, spreadsheets, documents, and slideshows. Secondary data is provided with a time frame of the period the data were originally collected within by the company, whereas primary data have been collected at multiple points in time throughout 2020 until the first quarter of 2022.

A notation of c, related to data sources, is used to reflect the component family the data concerns, ranging from the oldest $c = 1$ to the newest $c = 7$ which is in scope. $c \geq 4$ have more in common with $c = 7$ in terms of size, performance, and demand fluctuations with respect to v. Therefore, it is for reliability purposes desired to use sources $c \geq 4$ to the extent that data is available. For size-dependent variables, a mix of sources with calculations has been used which mainly relates to an upscaling of legacy data with the percentual difference in size relative to $c = 7$ denoted as $*\%\Delta$ respectively taking outset in the components' size in meters, or the systems' size in square meters. For inputs less dependent on size, the values have been applied directly. The scenarios $n \leq 3$, diverge on inputs related to the demand of components at regions i.e., dp_{vrt} and T. The latter differs due to availability where the data of historical demand for $c \geq 4$ used for $n \geq 2$ are limited to a ten-year horizon. In contrast, the forecasted demand for $c = 7$ is limited to a five-year horizon. The scenarios $n = 4, 5$ both apply an increase of the transport cost, whereas the latter also applies a reduction of spatial capacity. These scenarios are made, as it was desired by the company to evaluate under these conditions as they changed significantly during the Covid-19 pandemic.

An exemplified illustration of the case indices applied to the model and their interrelations is provided in Fig. 6. The network entities are shown as blocks, which from left to right refer to s, f, and r where a subset of f and r are delimited. Each entity uses units to produce units that are respectively referenced to the left and right of each entity. Specifically, the supplier uses systems to produce modules, whereas the factories use modules, in systems, to produce components. The colors refers to variants of units, and as the example has outset in the reconfigurable $d = 2$, only the varying systems and modules are provided with colors, as the remainder constitutes the common platform.

In Table 5, the values for rms_{mv} are provided. They specify variations in the system architecture with respect to the required modules of each configuration state, for $d = 1$ and $d = 2$ where indice $v = 0$ is delimited as no modules are required. No matter the design concept, four modules are required. However, what differs is the specific type of modules and the commonality in-between across states. With respect to $d = 1$ there is one-to-one mapping e.g. $v = 1$ requires $m = 1.1, 2.1, 3.1, 4.1$. Meaning the modules are dedicated without commonality. In contrast, $d = 2$ have commonality with respect to the first, third, and fourth module meaning that $m = 1.3, 3.4, 4.1$ are used across $v = 1, 2, 3, 4$. Thus, the reconfiguration of $d = 2$ is done by exchange of the third module where there are four possibilities i.e. $m = 2.1, 2.2, 2.3, 2.4$. This contrasts to $d = 1$, where reconfigurations require change of all modules.

In Table 6, the values for ldp_{fr} are provided. They specify if a factory is considered to be localized to regions or not. It is specified in binary terms, reflecting a yes or no answer.

In Table 7, an overview of the total demand volume along with the regional dispersion across the selected scenarios is presented. The primary difference is that $n = 1, 2$ relative to $n \geq 3$ have a higher volume and narrower dispersion. The volume difference occurs due to a longer covered lifetime, which was possible with historical data. However, the remainder is explained by a trend of volume being increasingly fragmented across variants with new family introductions. The difference in dispersion occurs due to an increased number of countries being served. The demand were primarily concentrated in Europe for $n < 0$, America for $n = 1$, and in Europe for $n = 2$. Currently, the products have generated global recognition, why an expected dispersion is projected for scenarios $n \geq 3$. Due to confidentially, additional insights on the demand cannot be provided with specific numbers or illustrations hereof. However, there are two more primary differences. One is the sequence of variant introductions in the family, which have transitioned from sequential with years in-between for $n = 1$ to parallel introductions

Table 5
Architecture of modules across system variants: rms_{mv}.

v	$m \in d = 1$				$m \in d = 2$			
1	1.1	2.1	3.1	4.1	1.3	2.1	3.4	1.3
2	1.2	2.2	3.2	4.2	1.3	2.2	3.4	1.3
3	1.3	2.3	3.3	4.3	1.3	2.3	3.4	1.3
4	1.4	2.4	3.4	4.4	1.3	2.4	3.4	1.3

Table 6
Localization index between factories and regions: ldp_{fr}.

	cn	*in*	*tr*	*de*	*it*	*es*	*us*
as	1	1	0	0	0	0	0
eu	0	0	1	1	1	1	0
na	0	0	0	0	0	0	1
la	0	0	0	0	0	0	0

Table 7
Volume dispersion of regional product demand: dep_{vrt}.

Scenario	Volume	*as*	*eu*	*na*	*la*
$n = 1$	> 40k	16%	18%	59%	7%
$n = 2$	> 30k	8%	61%	18%	12%
$n \geq 3$	> 10k	29%	15%	32%	21%

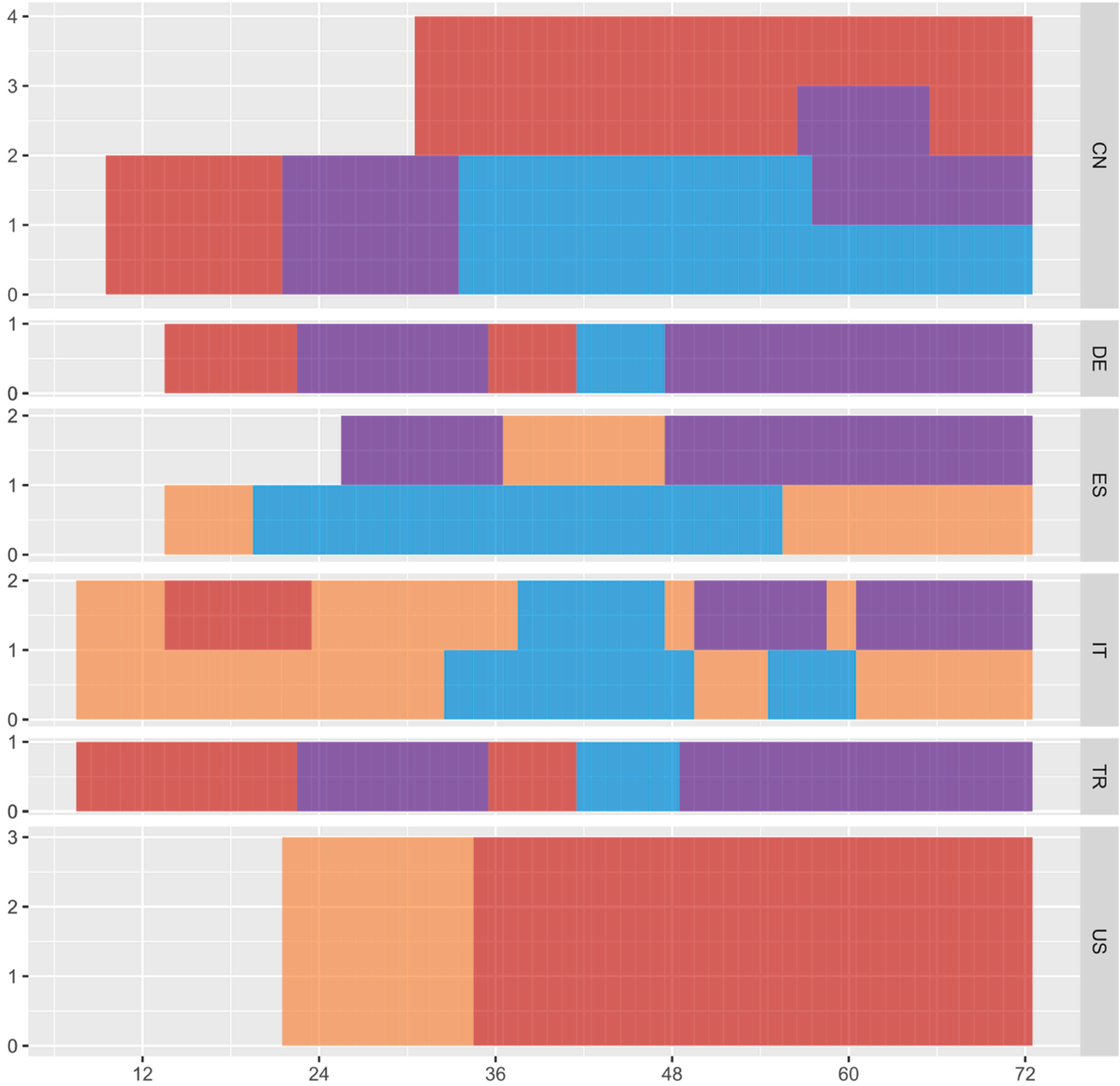

Fig. 7. Bar plot of configurations of production systems: cs_{vft} for the dedicated design: $d = 1$ in scenario five: $n = 5$.

for $n \geq 3$, whereas $n = 2$ is a mix of aforementioned. Another difference is the fluctuations with regard to timing. In general, the volume is unstable with weekly gaps in-between demand points, as it is project-based in a competitive market with reverse auctions. However, with the increased fragmentation of volume across variants, the timing gaps between demand points become increasingly apparent for new families.

6. Case results

The model was solved using Gurobi 9.1 on an i7–10610 U with 4 cores at 1.8 GHz where the optimality gap was set to $5e - 05$. The model, configured with d and n inputs, has between 27.720 and 55.440 integer decision variables and the total solving time ranged from 1017 to 1504 s.

6.1. Graphical plots

The configuration of systems, in terms of functionality and quantity across factories and periods, is illustrated in Fig. 7 and Fig. 9 for the dedicated and reconfigurable design. The plots are faceted according to factories where the x-axis is the time periods, the y-axis is the number of systems, and where the colors represent the functionality of systems for the production of component variants.

The production of products, with respect to variety and volume across factories and periods, with the production capacity hereof, is illustrated in Fig. 8 and Fig. 10 for the dedicated and reconfigurable design. The axes, facets, and colors hold the same connotation as in Fig. 7 and Fig. 9, where the line refers to the respective production capacity for products, which is aggregated according to variety. The difference between the colored area and the marked line reference non-utilized production capacity.

A comparison of the profiles for $d = 2$ relative to $d = 1$ reveals differences in terms of functionality and capacity, and the respective convertibility and scalability hereof, throughout time periods across factories. For capacity, the number of systems is reduced by two: specifically, those in $f = es$ which remain inactive. For scalability, one system for $f = cn$ is installed at a later point in time in a step-wise manner: 6 months after the predecessor. For functionality, an additional variant is configured and produced in $f = cn$ at two points in time, and in $f = de$ at three points. For convertibility, increased sporadic patterns can be seen in $f = cn, de, it$. For instance, there are nine conversions at $f = de$ in-between all variants for $d = 2$ which contrast to five in between three for $d = 1$. In terms of conversion to scale capacity of certain variants, an increase in terms of step-wise patterns can be seen. For instance, $d = 1$ configures two purple system variants between $t \sim 20$ and $t \sim 30$ whereas $d = 2$ first configures one, then scales that to two for 3 time periods before scaling down once again.

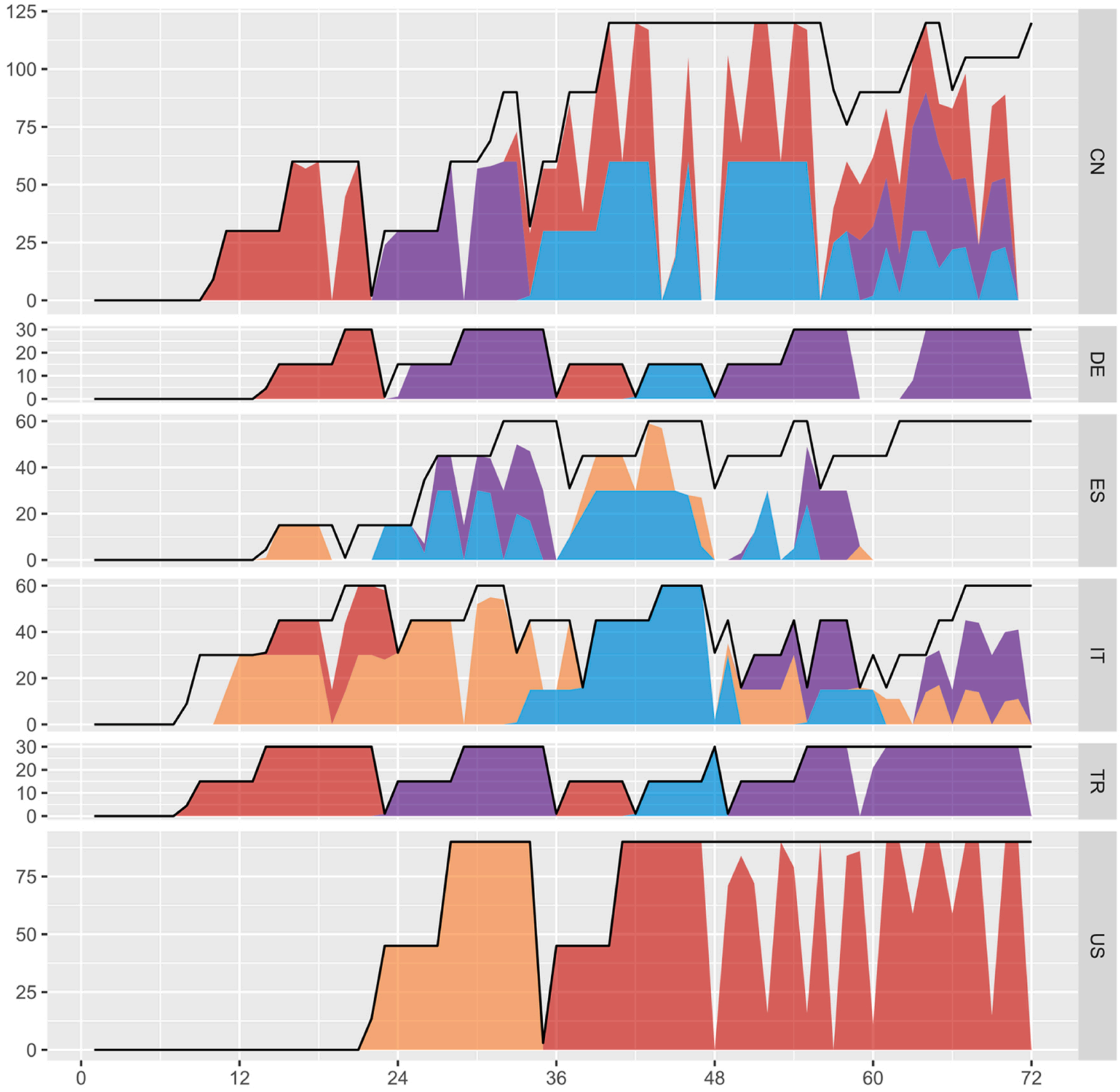

Fig. 8. Area plot of production mix of components: pp_{vft} with line plot of related production capacity utilization: pcp_{ft} for the dedicated design: $d = 1$ in scenario five: $n = 5$.

6.2. *Numerical results*

In Table 8, the performance of the reconfigurable design relative to the dedicated is outlined. The performance is measured on the set of objectives and parameters within each scenario and the yearly average across scenarios. All are measured as a percentual difference, whereas the objectives are also measured with respect to the monetary difference. All values are rounded to the nearest integer, except for values > 10% or > 10 m€ for simplicity.

6.2.1. *Performance across scenarios*

The reconfigurable design reduces the total cost with $\sim 1 \pm 0.5\%$ which amounts to ~ 10 m€/y. The difference in percent is $\sim 37 \pm 5\%$ for capex and $\sim 0.5 \pm 0.5\%$ for opex, whereas the monetary difference is near-equally divided.

For opex, the difference is primarily driven by a trade-off between transportation and production cost of products, which occurs as the demand fluctuates causing production to factories in vicinity which decrease the transport cost by ~ 7 m€/y and increase the production cost by ~ 3 m€/y. Aforementioned is driven by a slight increase in localized production, related to the minor increase of factories' functionality range, enabled by the major increase in the number of reconfigurations. Although, the latter is almost doubled, the required resource inputs is halved, which explains the minor impact on the cost hereof.

With respect to capex, the difference is driven by one-third reduction of produced modules which corresponds to a saving of ~ 5 m€/y on the cost hereof. The number of complete systems is halved and the lifetime utilization of modules is increased by a fifth, due to increased reusability of the installed common modules during the subsequent reconfigurations. The number of varying modules increase slightly due to an increased number of reconfigurations with modules delivered directly, as opposed to the more than doubled number of reconfigurations using modules from inventory. The latter, seems contradictory, as the number of modules on inventory decreases by two-thirds. However, it can also

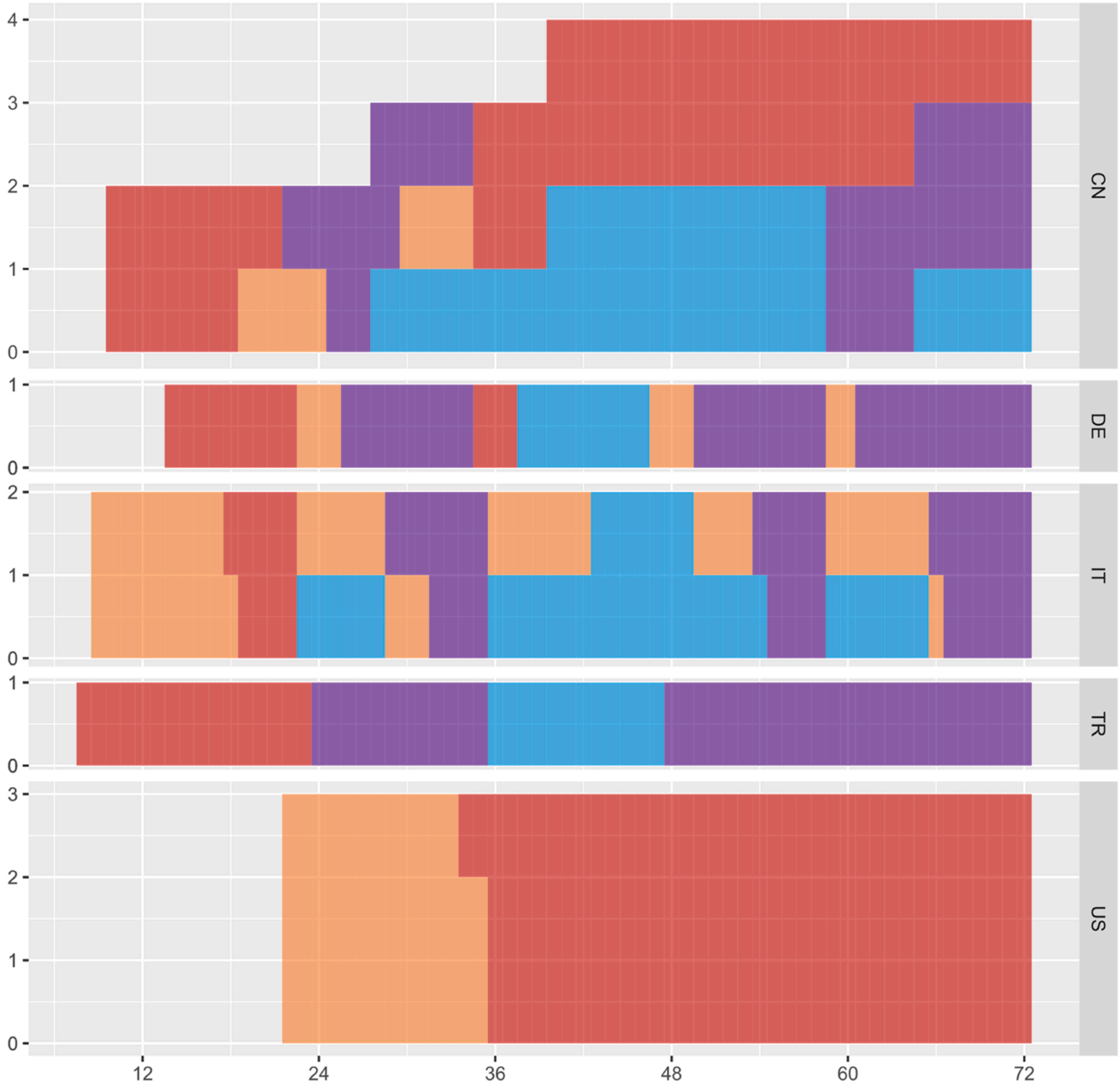

Fig. 9. Bar plot of configurations of production systems: cs_{vft} for the reconfigurable design: $d = 2$ in scenario five: $n = 5$.

be explained by the aforementioned increased reusability which imposes (i) fewer modules to inventory upon made reconfigurations and (ii) a decrease in number of delivered modules along with the cost hereof.

Due to reduced load of reconfigurations, the factories can operate with less system installations which also reduces the required production capacity and improves the related utilization. Similarly, the spatial capacity is also improved, even to the network where fewer factories are installed.

Within the supplier's operations, the required number of systems is reduced by a third which drives a similar impact on the production cost, although it is minor in terms of monetary value from a network perspective. However, the supplier's production load is still reduced, with a minor impact on the related lifetime utilization of their systems.

6.2.2. *Performance within scenarios*

The reconfigurable design outperforms on the majority of measures, although in some instances to a lesser extent, with few exceptions and differences in-between. The most critical in terms of monetary value is the production cost of products where the dedicated design outperforms, although with a trade-off on transport cost as previously outlined. However, in terms of $n = 5$, the reconfigurable mitigates the trade-off by creating positive values on both objectives: ~18 m€ and ~33 m€ respectively.

One explanation, is that the dedicated design limits the ability to execute reconfigurations, due to the increased time impact which can be mitigated throughout $n \leq 4$ by installation of additional systems which is limited in $n = 5$ due to spatial capacity. This implies that the reconfigurable design can enable an extent of changeability of the network to adapt back and forth between a focus on cost-efficiency of production and transportation, respectively.

A second explanation, although in line with the former, is that the dedicated design is forced to activate a factory to supply a region non-local region which effectively creates a situation where products are produced using high-cost labor and simultaneously transported across a high-cost distance to satisfy the demand. This is supported as the reconfigurable design reduces the number of installed factories by a fifth i.e., removal of factory = es. Further support arises upon comparison with the input from Table 7 where the demand volume of $n \geq 3$ is shown to be more evenly distributed across regions relative to $n \leq 2$ with a minority in $r = eu$ that is considered local to $f = es$.

Another exception concerns the number of products on inventory and costs hereof: both monetary and percentual, where the reconfigurable design is favored in $n \leq 2$ to a low extent, especially when considering that the horizon and volume of demand is doubled in comparison to $n \geq 3$. However, the dedicated outperform in $n = 3, 4$ where a possible explanation is that the reconfigurable builds up inventory in preparation for reconfigurations to reduce the cost of trans-

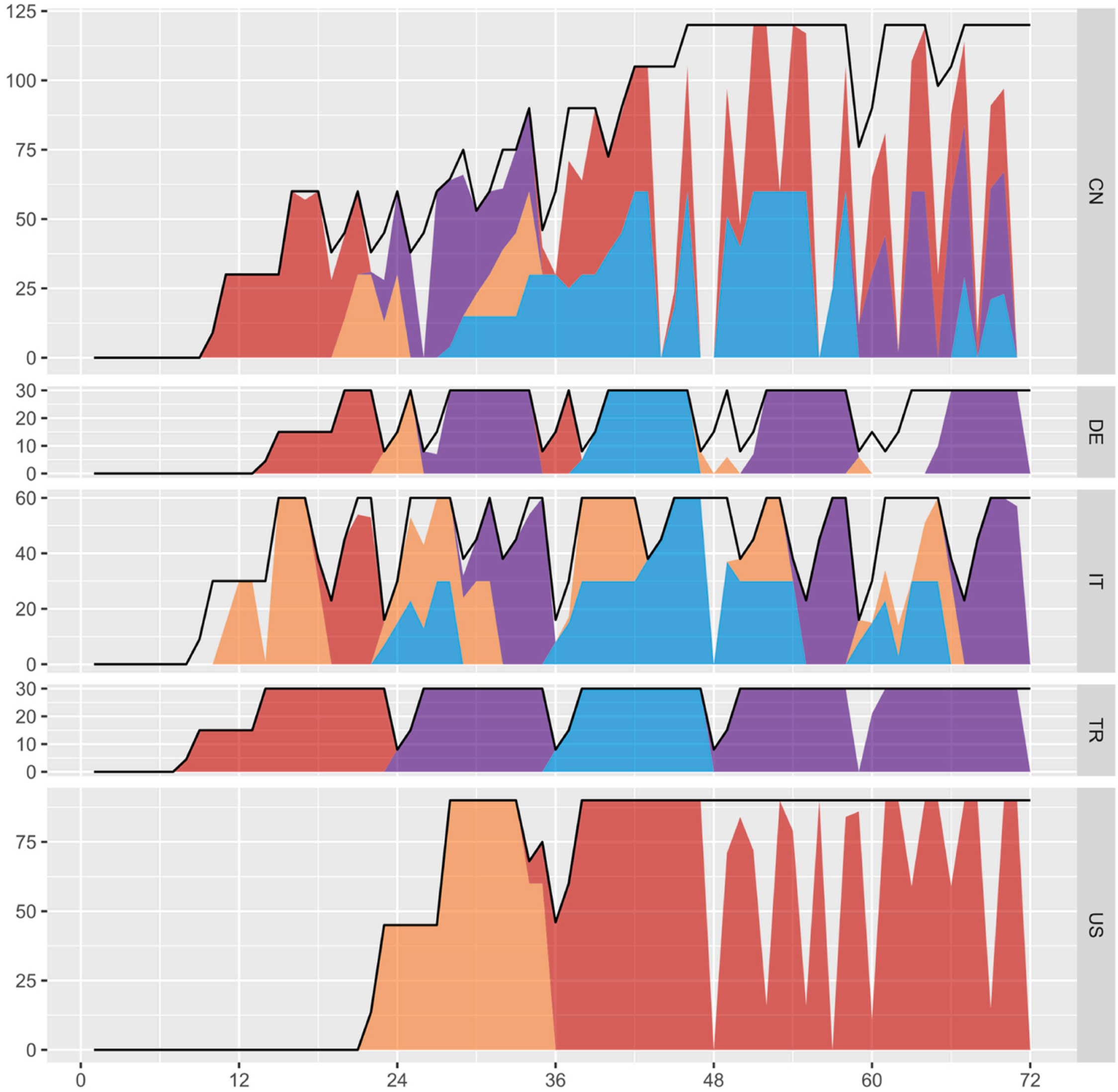

Fig. 10. Area plot of production mix of components: pp_{vft} with line plot of related production capacity utilization: pcp_{ft} for the reconfigurable design: $d = 2$ in scenario five: $n = 5$.

portation: indicating a second trade-off. Yet, the reconfigurable design outperforms by ~ 1 m€, about 6% in $n = 5$, which is near opposite as $n = 3, 4$. An explanation, is that the dedicated increases the number of reconfigurations in $n = 5$ relative to $n = 3, 4$, and thereby increase the capex, which indicates a third trade-off.

7. Discussion

7.1. Theoretical implications

7.1.1. The model

The primary theoretical contribution of this paper is the proposed optimization model with an application method to evaluate the expected performance impact, with respect to the capital and operational expenses of reconfigurable designs of production systems within a global production network of chained web structures.

In Table 9, the research gaps within state-of-the-art literature is summarized and compared to the included considerations of the proposed model. The first column lists 20 considerations in 6 categories, that are deemed necessary to include in the evaluation model by extant literature as previously discussed in Subsection 2.2. The second column summarizes the number of models within state-of-the-art literature that include the considerations, e.g. one of nine models support the scope of web-structure networks. The summation is calculated by adding the checkmarks across models for each consideration in Table 2. The delta, i.e. difference between the dividend and the divisor thereby reflects the number of models that delimit the considerations, which constitutes the research gaps, e.g. eight of nine models delimit the scope of web-structure networks. The extent to which a consideration constitutes a research gap thereby varies, since some are completely delimited e.g. the variable “production of system modules” whereas others are partially delimited e.g. the variable “reconfigurations of systems”. Therefore, a classification is applied to indicate the extent of the research gaps. Three classes of delimitation are created (h) high, (m) medium, and (l) low. With respect to the number of inclusions, the classification use the expression: $h \leq 3 < m \leq 6 < l \leq 9$. The severity of the research gaps is delimited from the classification, but is indicated in the argumentation that is provided in Subsection 2.2. The final column provides an outline of considerations that are included and delimited in the proposed model of this paper, which is respectively referenced by a check mark or a blank cell.

The proposed model mitigates 19 research gaps in total by merging the inclusions of the necessary considerations, which are dispersed across nine models in state-of-the-art literature. Of the mitigated

Table 8
Performance of d = 2 relative to d = 1 across scenarios.

	$\overline{n/y}$	**1**	**2**	**3**	**4**	**5**
Output parameters [Δ%]						
tps	-33	-38	-27	-33	-33	-33
tulcs	1.8	11	1.5	1.3		-5.0
tdm	-35	-32	-28	-36	-38	-42
tdcs	-51	-46	-40	-54	-56	-59
tdvm	7.5	5.6	4.8	13	11	3.7
tim	-64	-72	-68	-50	-59	-70
tif	-7.3			-20		-17
tirs	-16		-7.4	-31	-25	-15
tsrs	78	31	81	100	150	29
trsi	120	59	118	100	286	35
taff	7.3	2.5	10	-3.1	21	-6.6
tuscf	-16		-7.4	-31	-25	-15
tpcp	-13	4.3	-9.1	-25	-24	-8.6
tupcp	9.8	-3.0	7.4	19	18	6.9
tulcm	23	29	23	20	19	23
taip	1.2	-0.6	-1.7	6.2	5.7	-4.7
tldp	3.7	3.1	2.6	9.5	0.5	2.7
Economic objectives [Δ%]						
tpes	-20	-23	-16	-20	-20	-20
tpem	-38	-34	-31	-40	-41	-44
ttem	-11	-11	-8.1	-5.3	-14	-14
tres	-12	-21	-7.0	-10	-7.0	-29
tpep	0.3	0.3	0.2	0.9	0.6	-0.5
tiep	-0.2	-0.1	-1.9	3.6	4.9	-5.7
ttep	-2.8	-2.1	-1.7	-6.2	-2.0	-2.0
tcapex	-37	-33	-31	-39	-40	-42
topex	-0.4	-0.3	-0.1	-0.5	-0.1	-1.0
tcost	-0.9	-0.6	-0.4	-1.1	-0.7	-1.5
Economic objectives [Δm€]						
tpes	-0.1	-1.4	-0.7	-0.7	-0.7	-0.7
tpem	-5.3	-50	-37	-27	-31	-32
ttem	-0.2	-2.1	-1.1	-0.4	-1.3	-1.2
tres	-0.1	-1.4	-0.4	-0.3	-0.2	-1.2
tpep	2.8	35	26	33	24	-18
tiep	-0.0	-0.0	-0.7	0.6	0.7	-1.0
ttep	-7.3	-82	-39	-58	-31	-33
tcapex	-5.4	-51	-38	-28	-31	-32
topex	-4.8	-51	-16	-25	-7.8	-54
tcost	-10	-102	-54	-53	-39	-86

Table 9
Research gaps: summary of considerations within state-of-the-art (SOTA) literature compared to the proposed model.

Considerations	SOTA	Extent	Model
Scope			
Web structure network	1/9	*h*	✓
Approach			
Monolithic evaluation	7/9	*l*	✓
Uncertainty by scenarios	6/9	*m*	✓
Uncertainty by rolling horizon	2/9	*h*	✓
Objectives			
Minimize capital expenses	6/9	*m*	✓
Minimize operational expenses	7/9	*l*	✓
Maximize sales revenue	2/9	*h*	
Variables			
Reconfigurations of systems	6/9	*m*	✓
Production of products	9/9	*l*	✓
Production of system modules	0/9	*h*	✓
Inventory of products	3/9	*h*	✓
Inventory of system modules	0/9	*h*	✓
Transport of products	4/9	*m*	✓
Transport of system modules	3/9	*h*	✓
Limitations			
Ramp-up capacity of systems	2/9	*h*	✓
Lifetime capacity of systems	2/9	*h*	✓
Spatial capacity of factories	3/9	*h*	✓
Validation			
Validated in a real industrial case	6/9	*m*	✓
Sufficient extent of horizon	4/9	*m*	✓
Sufficient granularity of horizon	4/9	*m*	✓

research gaps, ten are of a high extent, seven of a medium extent, and three of a low extent. There is only one consideration which remains a research gap in the proposed model which concerns the objective to maximize sales revenue. This inclusion would increase the ability of the evaluation to capture the potential of reduced time-to-market. Mitigation of this limitation is discussed in Subsection 7.3.

A top contender in the *h* class concerns the scope of the most common network phenotype i.e. web-structures [8], which accounts for a share of ≥ 30% in industry [9] and is suggested as the phenotype of the future [2]. It is solely the preliminary model by *Kjeldgaard et al.* [47] which supports evaluation of reconfigurable production system designs in this most prominent type of production network. Yet, this model is only applicable for a partial evaluation as it delimits eight *h* class and two *m* class considerations. The proposed model also contributes to the call for research on addressing new mixed phenotypes of GPNs as suggested by Lanza et. al [2]. Although, the case application solely includes one system supplier, it can easily be expanded to chain of web-structures as discussed in Subsection 7.2.

Another set of top contenders in the *h* class, concern the variables for production, inventory, and transportation of system modules from suppliers to factories. None of the state-of-the-art models include these variables related to the module supply, with the exception of transportation. This imposes issues for the evaluation [18,19,56,57]. The severity is indicated, as it is critical to consider the supply of modules [18] and the impact on the system supplier's operations [19], as it can constrain the production capacity of products at the factories and create a risk of increasing the time-to-market and the backlog of orders [58,59]. Although some models consider the transportation, they assume that a limited and fixed set of modules within the network are sufficient. However, these constraints needs to be accounted for [18,19], as they can influence the adaptability and resilience of the production network. Since the proposed model includes the variables, it can be used to evaluate the impact of the supply along with the lead-time and capacity constraints and associated risks. Moreover, the variables extend the scope of the network to a chain of two web-structures with many interrelations: thereby enabling evaluation in a mixed phenotype.

The last set of top contenders in the *h* class concern the limitations of lifetime capacity of systems, spatial capacity of factories, and ramp up capacity of systems, which are all critical to consider in capital-intensive industries [28,37]. The majority of models delimit these limitations, whereas the proposed model includes them. This allows to capture the impact on production capacity and responsiveness of a factory and the network [11,37,38] along with the benefit of production localization in response to fluctuations of the demand [18,27,28], as well as a more accurate evaluation of the required number of investments [10,33].

7.1.2. The case results

The secondary theoretical contribution of this paper is the case results. The results contributes to the theoretical domain of global production networks and reconfigurable production systems, along with their interconnection.

Lanza et al. [2] suggested to investigate the adaptability of GPNs. In fact, they state that the role of adaptability must be addressed as it is within the core task of the design of GPNs. In this regard, adaptability is defined as the ability to respond to changes and uncertainty in the environment. Moreover, it has also been suggested that reconfigurable production systems can enable and facilitate adaptability of GPNs [4,11,14,23,64–67]. However, there are deficits within the state-of-the-art literature with respect to the quantitative results that demonstrate the adaptability of GPNs and evaluate reconfigurability as an enabler [2]. The case results, contributes with industrial insights on the adaptability of a web-structure phenotype in the capital goods industry, and the advantages of reconfigurable production systems. In the case, adaptability is the ability to make changes across multiple factories and systems of the GPN to rapidly and cost-efficiently respond to changes in the uncertain demand. The reconfigurable design of production systems enabled an 80% increase in the number of changes for a reduction of capital expenses and transportation expenses by 7.3 $\mathrm{m}€/y$ and 5.4 $\mathrm{m}€/y$, respectively. These results demonstrate the adaptability of GPNs and its enabler of reconfigurable production systems as key competitive factors on cost. In return, the results also contribute to support the theoretical proposition by Lanza et al. [2] related to harmonization of the production strategy and network. The paper supports the proposition that the theory of production strategies should be expanded from simple dyadic strategies of close-to-market production to reduce transport expenses, consolidated production to reduce investment expenses, and offshore production to reduce labor expenses. The case result show that a mix of these strategies is advantageous and that the mixed strategy can be enabled by the adaptability of GPNs through reconfigurable production systems. Specifically, in the disruptive scenario $n = 5$, the resilience generated by the adaptability through reconfigurability enabled the simultaneous reduction of capital expenses, production expenses, and transportation expenses by 32 m€, 18 m€, and 33 m€, respectively. These are also directly aligned with, and thus supports, the top-three tangible benefits of GPNs that are proposed by Ferdows [68]. The facilitated adaptability of GPNs enabled by reconfigurable production systems, also extends the seminal proposition of Koren [6], as reconfigurability is demonstrated to not merely provide "*exactly the capacity and functionality needed, exactly when needed*" yet also exactly where needed, in order to "*deliver the desired product, in the correct quantity, at the correct time, at the right place*", from the right place, as well. This is supported by the 3.7% increase of localized production which reflects components that are produced with closet vicinity to the market. This also impacts the transportation expenses that were reduced by 7.3 $\mathrm{m}€/y$. In scenario $n = 3$, the numbers were 9.5% and 11.6 $\mathrm{m}€/y$, respectively.

In recent years, further research have been proposed on enablers which can facilitate resilience of GPNs towards disruptions imposed by black-swan events [1] e.g., natural disasters, logistical blockages, wars, and pandemics [7]. In this regard, resilience is defined as the adaptive capability to prepare for unexpected events, respond to disruptions, and recover from them [69]. This definition implies a strong connection between adaptability and resilience. The disruptions imposed by recent events include, but are not limited to, an increase of transportation cost: upwards of 500% depending on the industrial environment [70] along with reduced spatial capacity: due to shutdowns of factories [1]. The disruptions impacted the case-company, which led to the construction of scenario $n = 5$ in order to measure the resilience generated by the reconfigurable design. Specifically, the transportation costs were doubled and the spatial capacity was halved in scenario $n = 5$, relative to $n = 3$. A comparison of the total cost between the scenarios reveals a difference of 47 m€, which suggests that the reconfigurable production systems increase the resilience for the GPN. The results thereby support the findings within state-of-the-art literature on supply chain resilience as identified by Naimi et. al [12], Biswas et. al [65], Napoleone et. al [71], and Dolgui et. al [72].

7.2. Practical implications

The results presented in this paper were used as the global business case in a reconfigurability development project within the case-company. The model, data, and results were presented to and reviewed by stakeholders on multiple occasions to advance the project through two stage gates subsequent the conceptual design and detailed development phases. 18 stakeholders were involved in the review including: team leads, technical leads, technical designers, managers, directors, senior specialists, and a chief operating officer. Besides the case, the model has utility for large enterprises with web structures. Thus it is expected to have relevance in the capital goods industry for the energy, maritime, and aeronautic sectors.

As outlined in Section 5.1, the collaboration with the case company was motivated by an expectation to be tested. The expectation was, and still is, that the reconfigurable design of production systems can mitigate the investment-logistics tradeoff which is present in the industrial context.

From a logistics perspective, it is efficient to satisfy the demand from factories with closest vicinity to markets, due to the cost of transportation at $35 \leftrightarrow 430$ k€ of the components with a size of $\sim 10^2$ meters. However, this will require frequent changes of the production mix of factories due to the variety of components and a fluctuating demand with respect to the timing, variety, volume, and location. In contrast, from a investments perspective it is efficient to dedicate the production mix of the factories due to the reconfiguration time of 28 days, ramp-up time of 6 months, and capital expenses of > 2 m€, of the production systems with a size of $\sim 10^3$ square meters and a weight of $\sim 10^2$ tons, Moreover, the spatial capacity of factories constrains the number of production systems that can be installed within the factories which limits the functionality and capacity of the production mix of factories.

The investment-logistics tradeoff have changed in recent times due to several change drivers. First, there has been an increase in the variety and size of components and their production systems due to intensified competition on the performance of products in the capital goods industry. Further, due to the requirement for customized products to the environmental conditions of an expanding number of markets to cater for, in order to win orders and increase the revenue. Secondly, the pressure for the localization of production has increased due to increasing requirements for local content to qualify for orders and increase revenue. Moreover, aforementioned is also due to macroeconomic factors such as natural disasters, logistical blockages, wars, and pandemics with implications that have increased (i) the cost and restrictions of transportation, (ii) the national protectionism, and (iii) shutdowns or reassignments of factories due to lack of materials and labor [1,7]. Thirdly, the fluctuations of the demand have increased with respect to the timing, variety, volume, and location. This occurred due to the aforementioned increase in number of markets to serve and the increase in the variety, size, performance, and volume of products to deliver whereas the timing is influenced by the combination of aforementioned that is related with a decrease in the size of orders and batches.

The case company produce the production systems and is thereby vertically integrated across tiers of the network within respective domains. Therefore, the impact on the operations of the system supplier and their constraints to supply modules to the factories for reconfigurations was also considered. The design was expected to increase the lifetime utilization of modules, that impose a comparably decreased load on the supplier's production capacity and the capital expenses to achieve it. Moreover, due to the systems' size and weight which impacts the time and cost transportation, especially with high-volume requirements of modules, it was sought to include their transportation as well, as the volume is expected to decrease.

The results are overall in line with the expectations as the reconfigurable design mitigates the investment-logistics trade-off. This is suggested by the average simultaneous reduction of capital expenses with 7.3 $\mathrm{m}€/y$ and transportation expenses with 5.4 $\mathrm{m}€/y$. The former occurs due to the 35% reduction of investments, enabled by the 51% increase of reusability, the 23% increase of life-time utilization, the 9.8% increase of capacity utilization, and the 16% reduction of installations and spatial capacity. The latter occurs due to the 3.7% increase of production localization that is facilitated by the increased adaptability: measured on the 78% increase in reconfigurations and the 7.3% increase in functionality range. It were expected that production expenses increased, due to the offshore trade-off related to increased labor expenses in favor of reduced transportation expenses, albeit the average increase of 2.8 $\mathrm{m}€/y$ were much lower than expected. However, it was somewhat unexpected that the resilience generated by the reconfigurable design could mitigate the offshore trade-off in the disruptive scenario $n = 5$. Here the production and transportation expenses were simultaneously reduced by $\sim$18 m€ and $\sim$33 m€ respectively. The possible reasons are previously discussed in Section 6.2.2. In summary, the reconfigurable design enabled the GPN to adapt back and forth between a focus on cost-efficiency of production and transportation, when the spatial capacity were limited and the transportation expenses increased. This contrasts with the dedicated design, which required the activation of an additional factory with increased transportation and labor expenses to satisfy the demand of a non-local region. Regarding the impact on, and the influence of, the system suppliers' operations, the results suggests confirmation, rejection, and uncertainty with respect to the expectations of the company. The reduced production load of 33% was in line with expectations, whereas the increase of lifetime utilization of 1.8% were disappointing. The latter was discussed and scrutinized. The presumable explanation is the combination of a high production load at 110 units on average, relative to a low lifetime capacity of 10 units. The impact of the supply constraints on the (re-)allocation of production across factories to supply fluctuating demands, was uncertain and could not be retrieved from the results. However, during experimentations with the parameters of the rolling horizon heuristic, it was identified that the model could not be solved if either the horizon or window were too narrow. This is presumably due to the lead-time of the supply of modules which constrains the production of products in a way so that the demand cannot be met in the time required by the market. If the impact was to be measured, it can be done by a modified model so that the no-backlog constraint is removed while also incorporating an opportunity cost with regards to the shortage or backlog of orders. This is discussed further in Section 7.3.

Another unexpected occurrence concerns the inventory of products and the expenses hereof. In scenario $n = 3, 4$, the reconfigurable design builds up inventory in preparation for reconfigurations to reduce the cost of transportation. This contrast to scenario $n = 5$, where the dedicated increased the number of investments relative to $n = 3, 4$. These occurrences can be summarized as the unexpected mechanisms and patterns of the designs, with respect to a polylemma of costs with regards to production, inventory, transportation, and investments across domains and tiers. Hereby, the results not only provided the value of a global business case, but also highlighted unknown unknowns.

Although the model has the objective to evaluate designs, it can also be applied in the subsequent implementation. Specifically, it provides utility within the planning domain to support both tactical and strategic decisions regarding the allocation, reconfiguration, and investment decisions across factories, as it essentially creates a production and logistics plan with a monthly granularity. Scenarios can also be used here to plan aforementioned with projected uncertainties of products and disruptions. It is especially relevant due to the introduced complexity and opportunity that arise with reconfigurability. In the case, it created the aforementioned polylemma which is of interest for further research in terms of reconfigurable production systems as a feasible mitigation strategy.

7.3. Limitations

The case results demonstrated the utility of the model for comparative evaluation against a dedicated system design. In contrast, a flexible design can be modeled by modifying the input rms_{mv}, exemplified in Table 5, to an architecture with a common module required across system variants.

The utility was shown for a web structure network. Yet, it is possible to model chained web structures, of suppliers to factories to regions, by an expansion of the supplier indices across the constituents and interrelations. It can improve the production capacity and transportation time.

Moreover, the utility was shown in a case with new designs of systems. Yet, it is also possible to input systems already in operation, but in the functionality range of the design. This can be done by modification of the input sc_f to sc_{vf} and delimitation of $v = 0$ for $\mathrm{cs}_{vft}, t = 0$in Eq. (39). These systems could be the subjects for reconfigurations, without supply constraints. This, and aforementioned, can improve the responsiveness and time to market for GPNs.

To capture the potentials of reduced time to market, i.e. improved revenue, opportunity costs and backlog costs, requires (i) specification of the inputs and sub-objectives, (ii) delimitation of the demand constraint in Eq. (24), and (iii) modifications to the objective in Eqs. (1–2) to a maximation of profit if revenue is included, as opposed to retaining minimization if including an opportunity cost.

The production systems are modeled as their hardware constituents that delimit the influence of logical aspects on the results. Specifically, workforce mechanisms have been delimited i.e. hire, fire, size, shifts, overtime, temp workers, capabilities, training time, retention time, and availability. Functionality and capacity are thereby solely dependent on the equipment, where the workforce is delimited as a potential bottleneck. In practice, it might be infeasible, either skill-wise or economically, to enable the changes in production mix across factories, generated by the model, which is a primary component of the case results.

The inclusion of workforce and production mechanisms at the system supplier would impose limited capacity and thereby potential scarcity of system modules throughout the network. This can necessitate transport of modules in-between factories in order to win orders by meeting local content requirements. Capturing the potentials hereof, requires introduction of (i) a new decision variable tm_{mfft} which are added and subtracted from am_{mft} for respective factories, along with inputs to calculate the time of delivery within a new variable and cost of transportation within a new sub-objective; and (ii) demand localization constraint between delivery from factories to demand of regions with respect to dp_{vfrt} and dep_{vrt}. The former would enable modelling of the storage, distribution, and sharing of modules for reconfiguration across the network to satisfy urgent needs. This has been proposed for further research to identify strategies in the context of disruptions [11].

8. Conclusion and further research

The objective of this paper was to construct and apply a model to evaluate the expected performance impact with respect to the capital expenses and operational expenses of reconfigurable designs of production systems within a global production network. The theoretical contribution is an optimization model with an application method that resolves multiple research gaps. The most critical are: (i) support for web-structures, (ii) inclusion of variables for the production, inventory, and transportation of system modules, and (iii) inclusion of capacity limitations with regards to the ramp-up and lifetime of systems; and the space within factories. The second theoretical contribution is the results of the application to a case in the capital goods industry. The results suggest that reconfigurable production systems reduce the capital and transportation expenses with 7.3 $\mathrm{m€}/y$ and 5.4 $\mathrm{m€}/y$ respectively, by facilitating increased adaptability and resilience of the global production network to change and uncertainty. The practical implications is that the model can be used as a tool to construct global business cases, test expectations, support decisions, and advance stage-gates within the development of reconfigurable production systems.

Further research is proposed on the following areas: (i) extension of the model to capture the time to market potentials and the impact of workforce mechanisms, (ii) application to more cases and scenarios to validate the utility of the model and enrich insights on the benefits of reconfigurability on a network level, and (iii) extension of the model to include stochastic parameters by mixed simulation and optimization models.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The research provided in this paper is conducted within *Manufacturing Academy of Denmark (MADE)* funded by the *Innovation Fund Denmark*. The authors acknowledge the assistance of *Tea Caroline Konnerup* in proof reading the equations.

Appendix A. Output parameters

In Eqs. (39–41) ps, pcp, and dm are respectively summated to tps, tpcp, and tdm which represents the total (i) number of produced systems at suppliers, (ii) capacity at factories, and (iii) number of delivered modules.

$$\mathrm{tps} = \sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{m=1}^{M}\mathrm{ps}_{mst} \tag{39}$$

$$\mathrm{tpcp} = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{v=1}^{V}\mathrm{pcp}_{vft} \tag{40}$$

$$\mathrm{tdm} = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{s=1}^{S}\sum_{m=1}^{M}\mathrm{dm}_{msft} \tag{41}$$

In Eqs. (42), (43) tdcs and tdvm are calculated. They are derivatives of tdm, and represent the total number of complete system deliveries and varying module deliveries, which are calculated for $m = 1$ and $m = 2$, respectively. In reconfigurable systems the former is a common module, and the latter a varying. In dedicated systems each module represent a complete system and a varying module.

$$\mathrm{tdcs} = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{s=1}^{S}\mathrm{dm}_{msft}, m = 1 \tag{42}$$

$$\mathrm{tdvm} = \sum_{t}^{T}\sum_{f}^{F}\sum_{s}^{S}\mathrm{dm}_{msft}, m = 2 \tag{43}$$

In Eqs. (44), (45) average inventory i.e. tim and tip are calculated by summation of iam or iap over $T - 1$.

$$\mathrm{tim} = \left(\sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{m=1}^{M}\mathrm{iam}_{mft}\right)\Bigg/(T-1) \tag{44}$$

$$\mathrm{tip} = \left(\sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{v=1}^{F}\mathrm{iap}_{vft}\right)\Bigg/(T-1) \tag{45}$$

In Eq. (46) tirs is calculated by summation of rs for $v = 0$ which represents total initial system reconfigurations i.e. from empty states. The subsequent reconfigurations i.e. between variants is represented by tres. In Eq. (47) trs is calculated by summation of rs for $v > 0$. In Eq. (48) trsim is calculated by tirs added with tsrs subtracted with tdvm. Thereby trsim adds up reconfigurations made without a related delivery of varying modules: reflecting reconfigurations made using modules from inventory.

$$\mathrm{tirs} = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{\tilde{v}=0:\tilde{v}\neq v}^{V}\mathrm{rs}_{\tilde{v}vft}, v = 0 \tag{46}$$

$$\mathrm{tsrs} = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{\tilde{v}=1:\tilde{v}\neq v}^{V}\sum_{v=1}^{V}\mathrm{rs}_{\tilde{v}vft} \tag{47}$$

$$\mathrm{trsim} = t\mathrm{irs} + t\mathrm{srs} - t\mathrm{dvm} \tag{48}$$

In Eq. (49) tif is a summation of installed factories, where installation is determined by a positive binary if the summation of cs for $v, t > 0$ is above zero. In Eq. (50) scu is calculated by summation of cs divided with sc for $v > 0$. It represent factories' utilization of space for systems.

$$\mathrm{tif} = \sum_{f=1}^{F} I\left(\sum_{t=1}^{T}\sum_{v=1}^{V}\mathrm{cs}_{vft} > 0\right) \tag{49}$$

$$\mathrm{scu} = \sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{v=1}^{V}\mathrm{cs}_{vft}/\mathrm{sc}_{f} \tag{50}$$

In Eq. (51) affp is calculated by a summation of the functionality range of factories divided with tif. The range of a factory is calculated by summation of positive binary values for $v > 0$ generated if the summation of cs for $t > 0$ is above zero. It represents factories' produced variety.

$$\mathrm{affp} = \sum_{f=1}^{F}\left(\sum_{v=1}^{V} I\left(\sum_{t=1}^{T}\mathrm{cs}_{vft} > 0\right)\right)\Bigg/\mathrm{tif} \tag{51}$$

In Eqs. (52–54) pcup, lus, and, lum are calculated: (i) pcup by summation of pcp divided with pp, (ii) lcus by summation of ps times lcs divided with pm, (iii) lcum by summation of dm times lcm divided with pp times cm. They represent utilization of capacity. The former concern the apriori production capacity of systems for products. The latter two concern the lifetime production capacity of (i) systems for modules and (ii) modules for products.

$$\mathrm{pcup} = \left(\sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{v=1}^{V}\mathrm{pcp}_{vft}\right)\Bigg/\left(\sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{v=1}^{V}\mathrm{pp}_{vft}\right) \tag{52}$$

$$\mathrm{lcus} = \frac{\left(\sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{m=1}^{M}\mathrm{ps}_{mst} * \mathrm{lcs}_{ms}\right)}{\left(\sum_{t=1}^{T}\sum_{s=1}^{S}\sum_{m=1}^{M}\mathrm{pm}_{mst}\right)} \tag{53}$$

$$\mathrm{lcum} = \frac{\left(\sum_{t=1}^{T}\sum_{f=1}^{F}\sum_{s=1}^{S}\sum_{m=1}^{M}\mathrm{dm}_{msft} * \mathrm{lcm}_{ms}\right)}{\left(\sum_{t=1}^{T}\sum_{f=1}^{F}\left(\sum_{v=1}^{V}\mathrm{pp}_{vft} * \left(\sum_{m=1}^{M}\mathrm{cm}_{mft}\right)\right)\right)} \tag{54}$$

In Eq. (55) tldp is calculated by a summation of dp times specified ldp. It represents total products delivered from factories local to regions. Degree of localization in-between can be specified as binary or with weight. Input values can be specified using distance, time, and/or cost.

$$\mathrm{tldp} = \sum_{t=1}^{T}\sum_{r=1}^{R}\sum_{f=1}^{F}\sum_{v=1}^{V}\mathrm{dp}_{vfrt} * \mathrm{ldp}_{fr} \tag{55}$$

References

[1] ElMaraghy H, Monostori L, Schuh G, ElMaraghy W. Evolution and future of manufacturing systems. CIRP Ann 2021;70:635–58. https://doi.org/10.1016/j.cirp.2021.05.008.

[2] Lanza G, Ferdows K, Kara S, Mourtzis D, Schuh G, Váncza J, et al. Global production networks: design and operation. CIRP Ann 2019;68:823–41. https://doi.org/10.1016/j.cirp.2019.05.008.

[3] Dolgui A, Ivanov D. Exploring supply chain structural dynamics: New disruptive technologies and disruption risks. Int J Prod Econ 2020;229:107886. https://doi.org/10.1016/j.ijpe.2020.107886.

[4] Zidi S, Hamani N, Kermad L. New metrics for measuring supply chain reconfigurability. J Intell Manuf 2021. https://doi.org/10.1007/s10845-021-01798-9.

[5] Piller F., Lehmann-brauns S., Schmidt F., Matischok L., Brachmann D., Madeja N. Corona and the Consequences Ten Propositions on the Future of Digital Business Models for Industry 4.0 in the Post-Corona Economy 2020. https://doi.org/10.2139/ssrn.3617816.

[6] Koren Y. Globalization and manufacturing paradigms. Glob. Manuf. Revolut. John Wiley & Sons, Ltd; 2010. p. 1–40. https://doi.org/10.1002/9780470618813.ch1.

[7] Chen J, Wang H, Zhong RY. A supply chain disruption recovery strategy considering product change under COVID-19. J Manuf Syst 2021;60:920–7. https://doi.org/10.1016/j.jmsy.2021.04.004.

[8] Meyer T, Jacob F. Network design: optimizing the global production footprint. In: Abele E, Meyer T, Näher U, Strube G, Sykes R, editors. Glob. Prod. A Handb. Strateg. Implement. Berlin, Heidelberg: Springer; 2008. p. 140–90. https://doi.org/10.1007/978-3-540-71653-2_4.

[9] Schreiber B., Brundin N. Managing Global Production Networks. 2015.

[10] Bortolini M, Galizia FG, Mora C. Reconfigurable manufacturing systems: literature review and research trend. J Manuf Syst 2018;49:93–106. https://doi.org/10.1016/j.jmsy.2018.09.005.

[11] Epureanu BI, Li X, Nassehi A, Koren Y. An agile production network enabled by reconfigurable manufacturing systems. CIRP Ann 2021;70:403–6. https://doi.org/10.1016/j.cirp.2021.04.085.

[12] Naimi MAl, Faisal MN, Sobh R, Sabir LBin, Al Naimi M, Faisal MN, et al. A systematic mapping review exploring 10 years of research on supply chain resilience and reconfiguration. Int J Logist Res Appl 2021;0:1–28. https://doi.org/10.1080/13675567.2021.1893288.

[13] Koren Y, Heisel U, Jovane F, Moriwaki T, Pritschow G, Ulsoy G, et al. Reconfigurable manufacturing systems. CIRP Ann 1999;48:527–40. https://doi.org/10.1016/S0007-8506(07)63232-6.

[14] Elmaraghy H, Wiendahl H-P. Changeability - an introduction. In: ElMaraghy HA, editor. Chang. Reconfigurable Manuf. Syst. London: Springer; 2009. p. 3–24. https://doi.org/10.1007/978-1-84882-067-8_1.

[15] Koren Y. General RMS characteristics. Comparison with dedicated and flexible systems. In: Dashchenko AI, editor. Reconfigurable Manuf. Syst. Transform. Factories, Berlin, Heidelberg. Berlin Heidelberg: Springer; 2006. p. 27–45. https://doi.org/10.1007/3-540-29397-3_3.

[16] Koren Y, Gu X, Guo W. Reconfigurable manufacturing systems: principles, design, and future trends. Front Mech Eng 2018;13:121–36. https://doi.org/10.1007/s11465-018-0483-0.

[17] Brunoe TD, Napoleone A, Andersen A-LL, Nielsen K. Impact of different financial evaluation parameters for reconfigurable manufacturing system investments. In: Dolgui A, Bernard A, Lemoine D, von Cieminski G, Romero D, editors. Adv. Prod. Manag. Syst. Artif. Intell. Sustain. Resilient Prod. Syst. Cham: Springer; 2021. p. 479–87. https://doi.org/10.1007/978-3-030-85902-2_51.

[18] Singh A, Gupta S, Asjad M, Gupta P. Reconfigurable manufacturing systems: journey and the road ahead. Int J Syst Assur Eng Manag 2017;8:1849–57. https://doi.org/10.1007/s13198-017-0610-z.

[19] Gadalla M, Xue D. Recent advances in research on reconfigurable machine tools: a literature review. Int J Prod Res 2017;55:1440–54. https://doi.org/10.1080/00207543.2016.1237795.

[20] Pansare R, Yadav G, Nagare MR. Reconfigurable manufacturing system: a systematic review, meta-analysis and future research directions. J Eng Des Technol 2021. https://doi.org/10.1108/JEDT-05-2021-0231.

[21] Francalanza E, Borg J, Constantinescu C. Development and evaluation of a knowledge-based decision-making approach for designing changeable manufacturing systems. CIRP J Manuf Sci Technol 2017;16:81–101. https://doi.org/10.1016/j.cirpj.2016.06.001.

[22] Bellgran M, Säfsten K. Production system development. Prod. Dev. Des. Oper. Prod. Syst. London: Springer; 2010. p. 77–108. https://doi.org/10.1007/978-1-84882-495-9_4.

[23] Wiendahl H-P, Elmaraghy HA, Nyhuis P, Zäh MF, Wiendahl H-H, Duffie N, et al. Changeable manufacturing - classification, design and operation. CIRP Ann 2007; 56:783–809. https://doi.org/10.1016/j.cirp.2007.10.003.

[24] Khanna K, Kumar R. Reconfigurable manufacturing system: a state-of-the-art review. Benchmark Int J 2019;26:2608–35. https://doi.org/10.1108/BIJ-05-2018-0140.

[25] Zidi S, Hamani N, Kermad L. Modularity metric in reconfigurable supply chain. IFIP Adv Inf Commun Technol, 634. IFIP; 2021. p. 455–64. https://doi.org/10.1007/978-3-030-85914-5_49.

[26] Andersen A, Brunoe TD, Nielsen K. Reconfigurable manufacturing on multiple levels: literature review and research directions. In: Umeda S, Nakano M, Mizuyama H, Hibino N, Kiritsis D, von Cieminski G, editors. Adv. Prod. Manag. Syst. Innov. Prod. Manag. Towar. Sustain. Growth, vol. 459. Cham: Springer; 2015. p. 266–73. https://doi.org/10.1007/978-3-319-22756-6.

[27] Andersen A-L, Brunoe TD, Christensen B, Bejlegaard M, Sorensen DGH, Nielsen K. Tailored reconfigurability: a comparative study of eight industrial cases with reconfigurability as a key to manufacturing competitiveness. In: Benyoucef L, editor. Reconfigurable Manuf. Syst. From Des. to Implement. Cham: Springer; 2020. p. 209–45. https://doi.org/10.1007/978-3-030-28782-5_11.

[28] Christensen B, Andersen A-L, Medini K, Brunoe TD. Reconfigurable manufacturing: a case-study of reconfigurability potentials in the manufacturing of capital goods. In: Ameri F, Stecke KE, von Cieminski G, Kiritsis D, editors. Adv. Prod. Manag. Syst. Prod. Manag. Fact. Futur. Cham: Springer; 2019. p. 366–74. https://doi.org/10.1007/978-3-030-30000-5_46.

[29] Kjeldgaard S, Napoleone A, Andersen A-L, Brunoe TD, Nielsen K. Changeable manufacturing: a comparative study of requirements and potentials in two industrial cases. In: Dolgui A, Bernard A, Lemoine D, von Cieminski G, Romero D, editors. Adv. Prod. Manag. Syst. Artif. Intell. Sustain. Resilient Prod. Syst. Cham: Springer; 2021. p. 452–61.

[30] Chaube A, Benyoucef L, Tiwari MK. An adapted NSGA-2 algorithm based dynamic process plan generation for a reconfigurable manufacturing system. J Intell Manuf 2012;23:1141–55. https://doi.org/10.1007/s10845-010-0453-9.

[31] Russo P, Holzner P, Rauch E, Vidoni R, Matt DT, Spena PR, et al. Requirements for the design of flexible and changeable manufacturing and assembly systems: a SME-survey. Procedia CIRP 2016;41:207–12. https://doi.org/10.1016/j.procir.2016.01.018.

[32] Kjeldgaard S, Andersen A-L, Brunoe TD, Nielsen K. Methods and models to evaluate the investment of reconfigurable manufacturing systems: literature review and research directions. In: Andersen A-L, Andersen R, Brunoe TD, Larsen MSS, Nielsen K, Napoleone A, et al., editors. Towar. Sustain. Cust. Bridg. Smart Prod. Manuf. Syst. Cham: Springer; 2022. p. 138–46. https://doi.org/10.1007/978-3-030-90700-6.

[33] Kuzgunkaya O, ElMaraghy HA. Economic and strategic perspectives on investing in RMS and FMS. Int J Flex Manuf Syst 2008;19:217–46. https://doi.org/10.1007/s10696-008-9038-8.

[34] Andersen A-L, Brunoe TD, Nielsen K, Bejlegaard M. Evaluating the investment feasibility and industrial implementation of changeable and reconfigurable manufacturing concepts. J Manuf Technol Manag 2018;29:449–77. https://doi.org/10.1108/JMTM-03-2017-0039.

[35] Bortolini M, Galizia FG, Mora C, Pilati F. Reconfigurability in cellular manufacturing systems: a design model and multi-scenario analysis. Int J Adv Manuf Technol 2019;104:4387–97. https://doi.org/10.1007/s00170-019-04179-y.

[36] Bortolini M, Ferrari E, Galizia FG, Regattieri A. An optimisation model for the dynamic management of cellular reconfigurable manufacturing systems under auxiliary module availability constraints. J Manuf Syst 2021;58:442–51. https://doi.org/10.1016/j.jmsy.2021.01.001.

[37] Niroomand I, Kuzgunkaya O, Asil Bulgak A. Impact of reconfiguration characteristics for capacity investment strategies in manufacturing systems. Int J Prod Econ 2012;139:288–301. https://doi.org/10.1016/j.ijpe.2012.05.012.

[38] Niroomand I, Kuzgunkaya O, Bulgak AA. The effect of system configuration and ramp-up time on manufacturing system acquisition under uncertain demand. Comput Ind Eng 2014;73:61–74. https://doi.org/10.1016/j.cie.2014.04.017.

[39] Gyulai D, Kádár B, Monostori L. Capacity planning and resource allocation in assembly systems consisting of dedicated and reconfigurable lines. Procedia CIRP 2014;25:185–91. https://doi.org/10.1016/j.procir.2014.10.028.

[40] Gyulai D, Kádár B, Kovács A, Monostori L. Capacity management for assembly systems with dedicated and reconfigurable resources. CIRP Ann 2014;63:457–60. https://doi.org/10.1016/j.cirp.2014.03.110.

[41] Gyulai D, Monostori L. Capacity management of modular assembly systems. J Manuf Syst 2017;43:88–99. https://doi.org/10.1016/j.jmsy.2017.02.008.

[42] Wörsdörfer D, Lutter P, Lier S, Werners B. Optimized modular production networks in the process industry. In: Dörner KF, Ljubic I, Pflug G, Tragler G, editors. Oper. Res. Proc. 2015. Cham: Springer; 2017. p. 429–35. https://doi.org/10.1007/978-3-319-42902-1_58.

[43] Becker T, Lutter P, Lier S, Werners B. Optimization of modular production networks considering demand uncertainties. In: Fink A, Fügenschuh A, Geiger MJ, editors. Oper. Res. Proc. 2016. Cham: Springer; 2018. p. 413–8. https://doi.org/10.1007/978-3-319-55702-1_55.

[44] Becker T, Lier S, Werners B. Tactical planning of modular production networks with reconfigurable plants. In: Kliewer N, Ehmke JF, Borndörfer R, editors. Oper. Res. Proc. 2017. Cham: Springer; 2018. p. 549–55. https://doi.org/10.1007/978-3-319-89920-6_73.

[45] Guo W, Tian Q, Jiang Z, Wang H. A graph-based cost model for supply chain reconfiguration. J Manuf Syst 2018;48:55–63. https://doi.org/10.1016/j.jmsy.2018.04.015.

[46] Tian Q, Guo W. Reconfiguration of manufacturing supply chains considering outsourcing decisions and supply chain risks. J Manuf Syst 2019;52:217–26. https://doi.org/10.1016/j.jmsy.2019.04.005.

[47] Kjeldgaard S, Jorsal AL, Albrecht V, Andersen A, Brunoe TD, Nielsen K. Towards a model for evaluating the investment of reconfigurable and platform-based manufacturing concepts considering footprint adaptability. Procedia CIRP 2021; vol. 104:553–8. https://doi.org/10.1016/j.procir.2021.11.093.

[48] Asmussen JN, Kristensen J, Steger-Jensen K, Wæhrens BV. When to integrate strategic and tactical decisions? Introduction of an asset/inventory ratio guiding fit for purpose production planning. Int J Phys Distrib Logist Manag 2018;48:545–68. https://doi.org/10.1108/IJPDLM-02-2018-0058.

[49] Wiendahl H-P, Heger CL. Justifying changeability. a methodical approach to achieving cost effectiveness. J Manuf Prod 2004;6:33–40. https://doi.org/10.1515/IJMSP.2004.6.1-2.33.

[50] Koren Y, Wang W, Gu X. Value creation through design for scalability of reconfigurable manufacturing systems. Int J Prod Res 2017;55:1227–42. https://doi.org/10.1080/00207543.2016.1145821.

[51] Koren Y, Shpitalni M. Design of reconfigurable manufacturing systems. J Manuf Syst 2010;29:130–41. https://doi.org/10.1016/j.jmsy.2011.01.001.

[52] Schuh G, Monostori L, Csáji BC, Döring S. Complexity-based modeling of reconfigurable collaborations in production industry. CIRP Ann 2008;57:445–50. https://doi.org/10.1016/j.cirp.2008.03.013.

[53] Elmaraghy W. Knowledge management in collaborative engineering. Int J Collab Eng 2009;1:114–24. https://doi.org/10.1504/IJCE.2009.027442.

[54] ElMaraghy W, ElMaraghy H, Tomiyama T, Monostori L. Complexity in engineering design and manufacturing. CIRP Ann 2012;61:793–814. https://doi.org/10.1016/j.cirp.2012.05.001.

[55] Bejlegaard M, ElMaraghy W, Brunoe TD, Andersen A, Nielsen K. Methodology for reconfigurable fixture architecture design. CIRP J Manuf Sci Technol 2018;23:172–86. https://doi.org/10.1016/j.cirpj.2018.05.001.

[56] Valente A. Reconfigurable industrial robots: a stochastic programming approach for designing and assembling robotic arms. Robot Comput Integr Manuf 2016;41:115–26. https://doi.org/10.1016/j.rcim.2016.03.002.

[57] ElMaraghy H, Moussa M, ElMaraghy W, Abbas M. Integrated product / system design and planning for new product family in a changeable learning factory. Procedia Manuf 2017;9:65–72. https://doi.org/10.1016/j.promfg.2017.04.008.

[58] Buergin J, Blaettchen P, Kronenbitter J, Molzahn K, Schweizer Y, Strunz C, et al. Robust assignment of customer orders with uncertain configurations in a production network for aircraft manufacturing. Int J Prod Res 2019;57:749–63. https://doi.org/10.1080/00207543.2018.1482018.

[59] Olivares-Aguila J, ElMaraghy W. System dynamics modelling for supply chain disruptions. Int J Prod Res 2021;59:1757–75. https://doi.org/10.1080/00207543.2020.1725171.

[60] Budinoff HD, Bushra J, Shafae M. Community-driven PPE production using additive manufacturing during the COVID-19 pandemic: survey and lessons learned. J Manuf Syst 2021;60:799–810. https://doi.org/10.1016/j.jmsy.2021.07.010.

[61] Scala P, Mujica M, Delahaye D. A down to earth solution: applying a robust simulation-optimization approach to resolve aviation problems. 2017 Winter Simul Conf 2017:2626–37. https://doi.org/10.1109/WSC.2017.8247989.

[62] Baker KR. An experimental study of the effectiveness of rolling schedules in production planning. Decis Sci 1977;8:19–27. https://doi.org/10.1111/j.1540-5915.1977.tb01065.x.

[63] Baker KR, Peterson DW. An analytic framework for evaluating rolling schedules. Manag Sci 1979;25:341–51. https://doi.org/10.1287/mnsc.25.4.341.

[64] Ahmad A, Masood T, Kousar R. Reconfiguring and ramping-up ventilator production in the face of COVID-19: can robots help ? J Manuf Syst 2021;60:864–75. https://doi.org/10.1016/j.jmsy.2020.09.008.

[65] Biswas P, Kumar S, Jain V, Chandra C, Engineering M, Kumar A, et al. Measuring supply chain reconfigurability using integrated and deterministic assessment models. J Manuf Syst 2019;52:172–83. https://doi.org/10.1016/j.jmsy.2019.05.008.

[66] Morgan J, Halton M, Qiao Y, Breslin JG. Industry 4. 0 smart reconfigurable manufacturing machines. J Manuf Syst 2021;59:481–506. https://doi.org/10.1016/j.jmsy.2021.03.001.

[67] ElMaraghy H, Schuh G, ElMaraghy W, Piller F, Schönsleben P, Tseng M, et al. Product variety management. CIRP Ann 2013;62:629–52. https://doi.org/10.1016/j.cirp.2013.05.007.

[68] Ferdows K. POM forum: transfer of changing production know-how. Prod Oper Manag 2006;15:1–9. https://doi.org/10.1111/j.1937-5956.2006.tb00031.x.

[69] Ponomarov SY, Holcomb MC. Understanding the concept of supply chain resilience. Int J Logist Manag 2009;20:124–43. https://doi.org/10.1108/09574090910954873.

[70] Carriere-Swallow, Y.; Deb, P.; Furceri, D.; Jimenez, D.; Ostry J. Shipping Costs and Inflation. International Monetary Fund; 2022.

[71] Napoleone A, Bruzzone A, Andersen A-L, Brunoe TD. Fostering the reuse of manufacturing resources for resilient and sustainable supply chains. Sustainability 2022:14. https://doi.org/10.3390/su14105890.

[72] Dolgui A, Ivanov D, Sokolov B. Reconfigurable supply chain: the X-network. Int J Prod Res 2020;58:4138–63. https://doi.org/10.1080/00207543.2020.1774679.