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# Holistic approach for integrating customers in the design, planning, and control of global production networks

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ABSTRACT

Given today's customer requirements in different market segments, companies are facing increased complexity when utilising their global production networks. To meet long-term corporate goals, the consideration of customer requirements at early production planning stages and during the order fulfilment processes becomes essential. A holistic approach for production network design, planning, and control is sought addressing stated matters on strategic, tactical, and operational level. In this paper, a decision-support model is introduced integrating product allocation and production and supply network (re-)design, followed by assignment of customer orders to plants and local (re-) scheduling. The model is applied in the aeronautics industry.



## Motivation

Rapid globalisation and the recent economic recession directly influence the production landscape, making it more complex and dynamic than ever [1]. Advancing customer demand for new product functions and product features leave production companies with no choice but to continuously increase their product variant portfolio [2]. Simultaneously, growing competition owing to new competitors from developing countries poses a challenge for established companies in the production industry [2]. To remain competitive in this highly volatile environment, and to be able to deliver high-quality products at low cost and prices on time, manufacturing companies need to optimally utilise existing and potential manufacturing capabilities [3,4].

In order to fulfil customer demand for more complex products, production companies are under pressure to cooperate closely with their suppliers, as well as with their customers [5]. The increased product variety and intensified customer involvement in the order fulfilment phase are among the main factors that increase production system and network complexity [6,2]. However, when information is provided by suppliers and customers at the right level of detail and at the right time, companies may be able to plan and control their production more accurately [5].

Increased complexity generated by product customisation and stakeholder involvement at different phases of production requires a holistic approach [7], supported by different-level decision support tools, which are to be integrated. These tools should aim at addressing customer requirements and at supporting the efficient operation of production networks [8]. Under these circumstances of bringing together heterogeneous data, novel flexible production control systems have emerged, integrating complex algorithms and information and communication technologies [9].

In practice, there are three main aspects in production networks, namely design, planning, and control. The design phase is mainly concerned with the network configuration, including issues related to the location of customers, plants, and suppliers, and the types of plants and suppliers that are needed to fulfil customer requirements [10]. The planning phase is mainly focused on the enterprise resource management, the initial configuration, the capacity, the inventory, and the complexity management [11]. Finally, the control phase is one of the most important steps which is mainly focused on the monitoring, coordination, and risk management of the network, aiming to re-configure the designed network in case of any disturbances, thus maintaining each performance at high levels [11].

A main challenge is to effectively integrate all these aspects and provide a holistic approach which is capable of managing the complexity of systems and networks, and of delivering high-

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performance production networks when involving customers. To achieve that, integration of different tools at different decision-making levels is important.

Towards that, the objective of this paper is to support production companies when facing increasing customer requirements in competitive environments by introducing an integrated decision-support model for the design, the planning, and the control phase of production networks, as well as by integrating information provided by relevant stakeholders in terms of suppliers and customers into the decision-support model.

Subsequently to the literature review on the design, planning, and control of the production network as well as customer integration into these phases in Section "Status quo of customer integration in the production network design, planning, and control", the developed decision-support model is introduced in Section "Decision-support model for customer integration in the design, planning, and control of production networks". The decision-support model application is illustrated in Section "Experimental results in the aeronautics industry", whereas the conclusion is presented in Section "Conclusion".

## Status quo of customer integration in the production network design, planning, and control

To address the challenges of a competitive market environment, the global era of production should be characterised by increased adaptability to changes [12]. In the new production paradigm of 'Industrie 4.0', information and communication technologies are required to meet the challenges of adaptability, and to support the efficient design, planning, and operation of production networks at strategic, tactical, and operational levels [13].

A production network is comprised by the internal production sites of a manufacturing company [14,15]. In contrast to a virtual enterprise, which is a temporary network of cooperating enterprises [16], a production network is operated by a single enterprise. Compared to social manufacturing, meaning that production service providers use social media and networks for cooperation among each other and with customers [17], the production in production networks is solely conducted by one enterprise. However, production networks may be enhanced by social media as it will be introduced in Section "Decision-support model for customer integration in the design, planning, and control of production networks".

Designing, planning, and operating global production networks encompasses a variety of tasks with distinctive focal points [18]. Several hierarchical frameworks exist in literature for classifying such tasks in production networks, such as the ones described in the publications by Fleischmann and Meyr [19], Miller [18], and Volling et al. [15], who used diverse classification criteria, such as the planning level and planning object (e.g. Fig. 1).

As illustrated in Fig. 1, in this article it is aimed to develop an integrated decision-support model which covers all relevant tasks in the framework presented by Volling et al. [15], except for layout planning. Layout planning can be performed autonomously at site level, on the basis that requirements from location and product allocation planning, as well as requirements related to capacities

| level \ object | **Structures** (Strategic) | **Capacities** (Tactical) | **Orders** |
|---|---|---|---|
| **Network** | Location planning | Allocation planning | Central planning & order promising |
| **Site** | Layout planning | Capacity deployment | Decentral planning |

**Fig. 1.** Classification of planning tasks [15].

and technology restrictions, are known. In contrast to the planning of structures and capacities, order planning concerns the fulfilment of actual customer orders that are individually specified in the case of built-to-order production [15]. By addressing these tasks in an integrated manner, the entire potential of available and potential production resources can be considered, while taking into account characteristics of products and production sites for advantageous production network design, planning, and control. However, no decision-support model exists so far which address all relevant tasks in an integrated manner, thus encompassing structures, related capacities, and actual customer orders at both the network and the site level [15]. In the following, an overview of a selection of integrated approaches in literature is given which addresses at least two of the stated tasks in an integrated manner.

Typically, decisions on structures and capacities are made in an integrated manner since they are strongly interrelated. The approaches presented in the publications of Than et al. [20] and Lanza and Moser [21] integrate the decisions on location planning and capacity deployment. In both approaches, existing and potential production network capacities are taken into consideration when structural decisions are made about new locations and localised capacities.

When only focusing on the capacity object, there are several approaches integrating allocation planning and capacity deployment decisions, such as the ones described on the publications of Inman and Jordan [22], Inman and Gonsalvez [23], and Wittek et al. [24]. These approaches aim at high resource utilisation when allocating products to production lines in existing production network structures.

In recent years, a high number of decision-support models has been developed, which integrate location and allocation planning decisions, as well as decisions to be made in capacity deployment tasks (e.g. [25–31]). The approaches were mostly applied on production networks in the automotive industry. Their high number illustrates the relevance of the integrated tasks to comprehensive decision making regarding production network structures and capacities. Further approaches which address structural and capacity decisions can be found in the literature review paper of [32].

At order level, several approaches in literature integrate the network level and the site level for order planning. Bruns and Sauer [33] present an approach for multi-site scheduling, in which decentralised scheduling activities are coordinated. Therefore, they consider central planning and order promising in terms of global predictive and reactive scheduling, as well as decentral planning in terms of local predictive and reactive scheduling [33]. Other approaches at order level are presented by Chan et al. [34], Chen and Pundoor [35], and Chen and Hung [36]; in their works, they assign orders to multiple sites considering the local scheduling problems.

Newly introduced complex algorithms and information, as well as communication technologies, can be applied to integrate customers into network design-, planning-, and control-related tasks. An approach showing different ways of integrating customers in production is presented by Sandmeier [37], encouraging decision makers to implement and evaluate the customer integration mechanisms. Information and communication technology-based tools and smart mobile applications can further support industry to integrate customers and to address their needs and goals [38,39]. The integration of customers at different phases of production allows companies to accurately and efficiently design and manufacture customised products, and to easily adapt to any changes. Additionally, customer feedback integration in production is strongly connected with different aspects of production planning, such as resource requirement prediction [40]. Modelling its effect has already become an issue which is discussed in the literature [41]. Integrating customer feedback in production control requires highly flexible production models, supported by agile software that may translate customer requirements at the operational level, and support decision making [9]. However, the product customisation and the integration of the customer at different phases increases the amount of generated data and information that should be considered by the planning and control tools, thus leading to increasing systems complexity [42,43].

## Decision-support model for customer integration in the design, planning, and control of production networks

In the view of this article, multi-level integration of tasks while involving customers can be described in the decision-support model, illustrated in Fig. 2. For the different planning horizons, novel decision-support tools can be applied in an integrated manner to increase the utilisation of existing and potential internal and external production resources. Additionally, integration of and socialization with customers can be enhanced on all planning horizons by customer involvement tools.

On strategic level, the design of the production network operated by a single manufacturing company is supported by tool (1) based on forecasted customer demand that is reflecting high-level customer requirements. The efficient operation in changing environments is secured by tool (2) which is supporting the monitoring and the redesign of the production network of a single manufacturing company and the supply network consisting of suppliers of the production network. During network operations, customer use feedback, gathered with tool (A) plays an integral part when making redesign decisions. In order to fulfil customer demand in an efficient way, it is essential that the production and supply network are designed with regard to the product portfolio potentially demanded by the customers. Therefore, customer use feedback should be used on the strategic level to anticipate the product-mix demanded in the future while also adapting performance metrics to regional markets' unique requirements. Decisions made on production network structures, capacity deployment, and allocations set limits to the solution space for the subsequent assignment and scheduling of orders, which are supported by the tools (3) and (4) on tactical and operational level. Customers may specify each option of the product configuration just-in-time during the order fulfilment process supported by tool (B) and may also follow the production status of their order supported by tool (C). Based on the current production status, orders can be rescheduled, which is supported by tool (5).

Depending on the tasks to be fulfilled, the decision maker can select the most promising tools to simultaneously increase overall network efficiency and customer satisfaction.

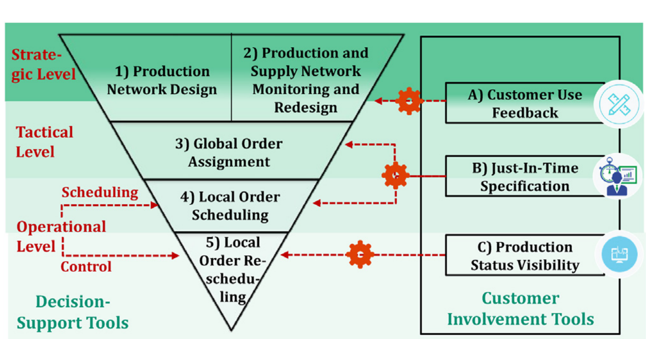


**Fig. 2.** Decision-support model for design, planning, and control of production network which integrates stakeholders.

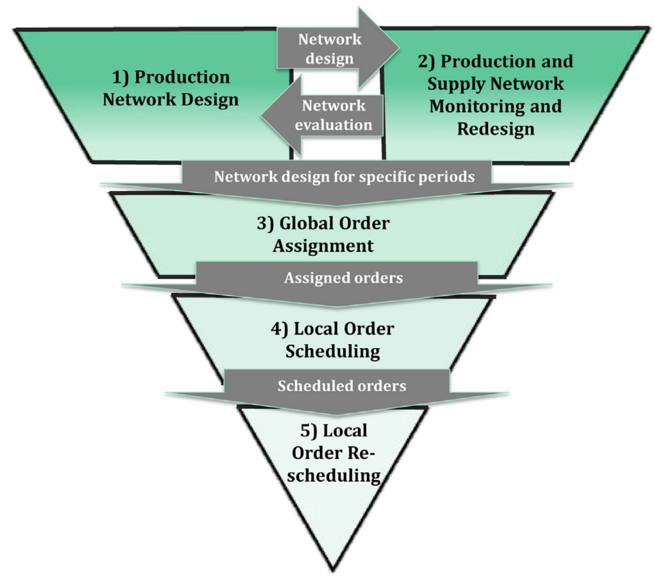


**Fig. 3.** Information sharing between tools of integrated decision-support model for the design, planning, and control of production networks.

The tools applied in the different planning horizons are integrated by sharing information as illustrated in Fig. 3. The output of the Production Network Design tool (1) is a network design which is used as input for the Production and Supply Network Monitoring and Redesign tool (2). The Production and Supply Network Monitoring and Redesign tool (2) provides an evaluation of the designed network that can be considered for the further production network design. The production network design implemented for specific periods provides the input for orders to be assigned to the sites of the network and to single periods by the Global Order Assignment tool (3). Consequently, the orders at each site for each period are locally scheduled by the Local Order Scheduling tool (4). The local schedules may be updated by the Local Order Rescheduling tool (5) based on the current production status.

### *Production Network Design*

In the Production Network Design tool (1), forecasted demand that reflects customer requirements towards the product portfolio is considered when deciding on production and supply network structures at a strategic level, and when deciding on product allocation and capacity deployment over a tactical planning horizon. Over planning horizons of several years, adaptability becomes necessary to enable stable performance under volatile market demand, particularly when dealing with fluctuations in production volume and product-mix [44].

Modelled as a multi-site, multi-process step, multi-product, multi-period mixed integer linear program (MILP), the product portfolio can be dynamically allocated to reconfigurable internal and external global production entities which feature a certain level of flexibility [45]. As illustrated in Table 1, flexibility and reconfiguration measures are implemented for production resources, for production segments, as well as at site and network level.

Flexibility measures include volume flexibility of staff resource groups (i.e. overtime, flexible resource allocation, as well as short-term and temporary increase in resource capacity) and external capacities. Furthermore, product-mix flexibility (ability to use one resource to build multiple products, according to Francas et al. [46]) and routing-flexibility (ability to produce a part by alternate routes through the system, according to Sethi and Sethi [47]) are

**Table 1**
Modelled adaptability measures.

| Adaptability category | Resource | Segment | Site/Network |
|---|---|---|---|
| Flexibility measure | Volume flexibility | Product-mix flexibility | Routing flexibility |
| Reconfiguration measure | Resource capacity adaption | Opening/closing | Opening/closing |
| | | Technology and shift model adaption | Transportation edge adaptation |

modelled to allow for the compensation of fully used capacities at one production site or segment. When flexibility measures can no longer cope with forecasted demand changes, there is a need for the reconfiguration of network structures and capacities. The decision space for reconfiguration of the network entities includes the opening/closing of sites and segments, the incorporation of suppliers through transportation edges, as well as alterations of production technologies and shift models implemented at segments. Additionally, the alteration of resource capacities, such as that of the permanent staff, and the use of new transportation edges between production segments, sites, and suppliers is modelled [45]. The Production Network Design tool aims at minimising the total operating cost *cO*, flexibility cost *cF*, and reconfiguration cost *cR* over a long term planning horizon in the objective function as illustrated in Eq. (1). The costs are determined by several decision variables included in Eq. (1) and listed in Table 2, accompanied by their meaning.

$$\min \sum_{t \in T} cO(x, L, RA)_t + cF(x, dOT, SlR)_t + cR(AprA, SA, SiA, CU, dRR, L)_t \quad (1)$$

In the following, a detailed description of the cost elements in relation to the relevant decision variable (in brackets) is introduced. The operating cost *cO* can be described as the sum of several cost items, including the direct supplier cost (*x*), the transportation cost (*L*), the direct labour cost (*RR*), the inventory cost (*x*), the fixed cost for technology localisation, and the usage of the production segment and maintenance of the production site (*x*). Meanwhile, the flexibility cost *cF* includes the cost of overtime (*dOT*), external production capacities (*x*), as well as the cost of a short-term and temporary increase in resource capacity (*SlR*). Accordingly, the reconfiguration cost *cR* consists of the cost of opening and closing sites (*SiA*) and of production segments (*SA*). Furthermore, the incorporation of suppliers through new transportation edges (*L*), alterations of production technologies (*AprA*), shift models (*CU*), and resource capacities (*dRR*) need to be considered.

The workflow of the Production Network Design tool is illustrated in Fig. 4.

The developed MILP is initialised based on the input in terms of the initial production network entities, the planning horizon, as well as the related costs and forecasted demand for the product portfolio. After solving the MILP using a branch and cut algorithm provided by standard optimization software such as CPLEX, sensitivity information on the optimal solution can be generated.

**Table 2**
Decision variables of the Production Network Design tool.

| Variable | Description |
|---|---|
| *AprA* | Production technology at production segment |
| *CU* | Shift model |
| *dOT* | Overtime |
| *dRR* | Alteration (+/−) in resource capacity |
| *L* | Transport volume |
| *RA* | Allocation of working time |
| *SA* | Activity of segment |
| *SiA* | Activity of site |
| *SlR* | Temporary resource |
| *x* | Amount of products to be processed |

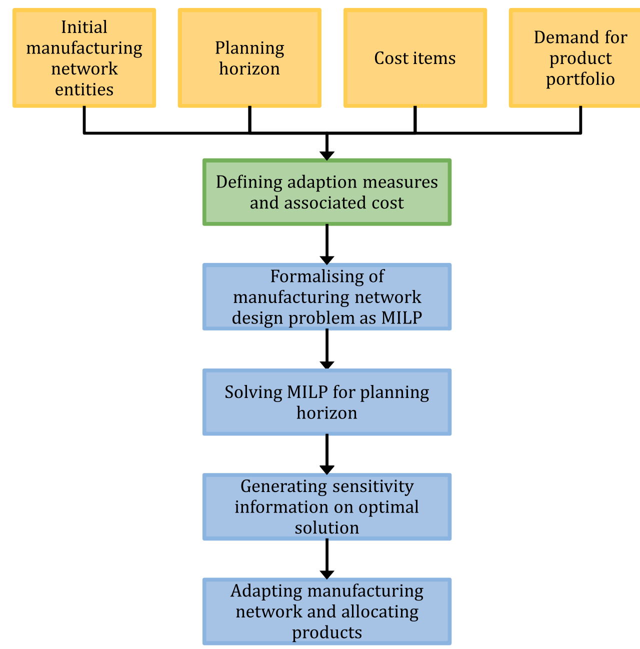


**Fig. 4.** Production Network Design tool workflow.

The output of the tool is the design of a production network and a product allocation, which might be an adaption of the initial production network and of the initial allocation of the product portfolio to the network entities.

*Production and Supply Network Monitoring and Redesign*

When designing a production network, partner selection is crucial in achieving the goals of the manufacturer, while securing constant supply of the required parts [48]. The presented approach focuses on the supply network design support and performance monitoring throughout production. In the second tool, the production and supply networks are monitored and redesigned, so as to secure their efficiency in changing environments. To redesign the production and supply network for a given order, the bill of materials (BoM) of the product is connected with the available suppliers and own production sites. The evaluation and redesign of the production and supply networks is performed using a decision-making algorithm, considering also customer feedback (tool (A)). The decision-making algorithm consists of several steps, as shown in Fig. 5.

The algorithm first receives as input the BoM, the bill of processes, and the list of suppliers and sites. Once the data are gathered, the suppliers are ranked based on defined criteria. The end-user defines the weights of these criteria, and the ranking is performed. As a next step, once the suppliers have been ranked, the alternative networks are generated. Based on defined criteria (total cost, lead time, quality, etc.), the value of each criterion for each alternative network is calculated. Finally, the utility value for each alternative is calculated, and the alternative with the highest value

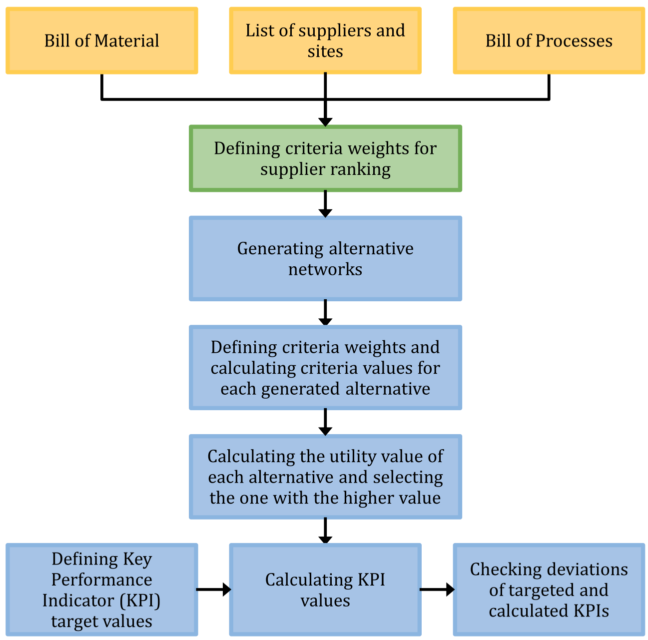


**Fig. 5.** Production and Supply Network Monitoring and Redesign tool workflow.

is selected as an output. To track the effectiveness of the network, the end-user is capable of defining target values to the key performance indicators (KPIs) of the generated network. Following that, the deviations among the calculated and the targeted KPIs are calculated and used as an output that will support the continuous monitoring of the network performance.

In both steps, the supplier ranking and the network alternatives generation the same criteria are considered for decision-making. Different weights are assigned to each criterion, reflecting the strategy of the original equipment manufacturer (OEM). The selected criteria are: (i) the total cost, (ii) the quality, (iii) the reliability, and (iv) the lead time. The equations used of each criterion for ranking the suppliers and determining the performance of an alternative production and supplier network configuration are the following:

i) Total cost: Where PC is the production cost of every operation that has been performed by an OEM, $DC_t$ is the delivery cost that is created from components that are bought from suppliers, $TC_r$ is the transportation cost for root r, where r is the number transportation roots (r = 1, 2, . . . , R); d is the number of tasks for one job (d = 1, 2, . . . , D), om = 1,2, . . . ,OM denotes operations MAKE, and ob = 1,2, . . . ,OB denotes operations BUY, Eq. (2).

$$Total\ Cost = \sum_{om=1}^{OM} PC_d + \sum_{r=1}^{R} TC_r + \sum_{ob=1}^{OB} DC_d \quad (2)$$

ii) Quality (QL): Where $QL_k$ is the quality of the supplier that performs task k. The quality is calculated as the average of the qualities of the supply chain partners that are selected in an alternative configuration. Based on empirical and historic data, the values of the qualities of the supply chain partners are obtained from the OEM of the case study are calculated using Eq. (3).

$$QL = \frac{\sum_{k=1}^{K} QL_k}{K} \quad (3)$$

iii) Reliability (R): Where $R_i$ is the reliability of each OEM node, and i is the number of assignments 1,2, . . . , N, as given in Eq. (4).

$$Reliability = \prod_{i=1}^{N} R_i \quad (4)$$

iv) Lead time (FLT): Where PT is the production time for OEM i to perform task k, TT is the transportation time from partner i to partner j, DT is the delivery time for supplier i to produce component m, p is a provider (supplier or OEM), and l is the number of levels of the BoM tree (l = 1, 2 . . . , L), calculated as in Eq. (5).

$$FLT = \sum_{l=1}^{L} \left[ \max_{p} (PT_{ik} + TT_{ij}, DT_{im} + TT_{ij}) \right] \quad (5)$$

To monitor the performance of the designed network, three influencing factors are to be checked. First, a set of carefully selected KPIs that cover different aspects of the network's impact (time, cost, quality, and energy efficiency) is monitored. Targeted KPI values are defined, based on the main goals of the company, and the deviation between the targeted and the actual values is calculated; a high deviation in these values is an indicator for network reconfiguration. All the criteria that were analysed above are considered as KPIs as well because the total cost, time, reliability and quality are important measurements that need to be taken into account.

In addition to that, the availability of the suppliers in the supply network and the availability of the manufacturing resources in the production network are monitored as well, to increase systems efficiency and adaptiveness. Whenever a supplier fails to meet the initially set deadlines, a new network is quickly designed using the developed algorithm. Finally, the customers' opinions are considered as a monitoring factor, which can be reflected by modifying the criteria weights based on the feedback gathered. Thereby the design of the network can be adjusted according to the feedback gathered with the Customer Use Feedback tool (A).

*Global Order Assignment and Local Order Scheduling*

During the order fulfilment process, customers are given the option to become further involved by granting them the choice to specify each option of the product configuration at the respective latest possible point in time. This service is referred to as the Just-In-Time Specification (tool (B)) [49–51]. This service can be offered in parallel to the global assignment or the local scheduling of orders determining which options are fixed and which are not at the time of planning [50].

Decisions made on production and supply network structures and capacities restrict the solution space for the consequent planning of customer orders in the Global Order Assignment tool (3). Global order assignment is a central planning task of assigning incoming customer orders to sites and periods in a global production network and can be formulated as an integer, i.e. binary, linear program (ILP) [52]. The binary decision variables $x_{ilt}$ determine the assignment of each order $i$ to site $l$ and period $t$. Therefore, the product model as the basic configuration of each order has to be fixed prior to global order assignment [50]. This is necessary to guarantee that the order can be assembled at the designated site, as a case may occur where not every product model can be assembled at all sites [50]. All further product options to be selected according to the Just-In-Time Specification tool (B) for customer involvement after global order assignment have to be handled by the sites the respective orders have been assigned to.

To effectively use resources that are available for production at each site during each period, the capacity supply $C_{lt}$ – herein referred to as capacity – in terms of hours of staff should equal the capacity demand resulting from assigned orders $i$ and their respective expected workload $E(w_{ilt})$ in hours, for each period $t$ at each site $l$. The expected workload can be derived for each order by calculating the sum over the workload of its product model – which is considered as deterministic when assigning orders globally – and the expected workload of its options – based on the workload of the options which are considered as stochastic when assigning orders globally. As the options are not fixed at the time of global order assignment in the case of offering the Just-In-Time Specification service, the expected workload of the options of an order can be used. The expected workload can be calculated by adding the workload of the product model to the sum of the probability for each potential option selection multiplied by the respective workload. Knowing the customer order of a capital good, historical data on customer option selection can be used for anticipating the probabilities for the option selection of current orders [52]. The modulus of the relative workload deviation between the expected workload and the workload capacity within one period at one site can be calculated by Eq. (6). Using the modulus allows for considering positive and negative deviations uniformly. Compared with the absolute deviation, the relative deviation allows for a comparison among workload deviations of different periods and at different sites with different capacities.

$$\frac{|(\sum_{i=1}^{I} E(w_{ilt}) \times x_{ilt}) - C_{lt}|}{C_{lt}} \tag{6}$$

Following the objective to minimise the modulus of the relative workload deviation within each period at each site to accomplish efficient use of resources still raises the question of how to formulate the objective function. The question is how to balance the workload deviations among periods and sites in the objective function when globally assigning orders. For example, in a case of only two sites and one period with the same capacity, would both having the same level of deviation be as preferred as one having more and the other having less deviation, but both having the same deviation in total. If this is the case, the overall objective function can be represented by the sum of the modulus of the relative workload deviations over all periods and sites, and it may be minimised, as presented in Eq. (7).

$$\min \sum_{t=1}^{T} \sum_{l=1}^{L} \frac{|(\sum_{i=1}^{I} E(w_{ilt}) \times x_{ilt}) - C_{lt}|}{C_{lt}} \tag{7}$$

On the contrary, not allowing a high deviation to be balanced with a low deviation, an alternative overall objective function is suggested, and is presented in Eq. (8). It minimises the maximum of the modulus of the relative workload deviations over all periods and all sites.

$$\min \max_{t,l} \left\{ \frac{|(\sum_{i=1}^{I} E(w_{ilt}) \times x_{ilt}) - C_{lt}|}{C_{lt}} \right\} \tag{8}$$

Therefore, either (a) the sum or, alternatively, (b) the maximum of the modulus of the relative workload deviations can be minimised in the objective function when assigning orders. The experimental results presented in the following sections allow for further discussion, after comparing both objective functions.

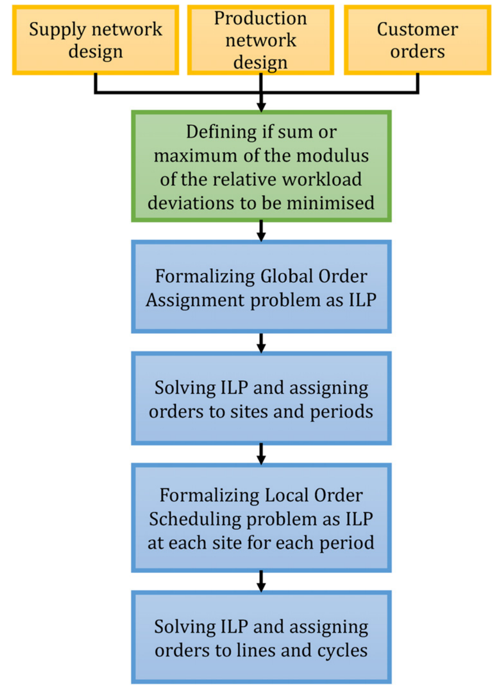


**Fig. 6.** Global Order Assignment tool and Local Order Scheduling tool workflow.

As illustrated in Fig. 6, decentral planning tasks of order scheduling take place at local sites for each period (Local Order Scheduling tool (4)) subsequent to the global order assignment. The design of the supply network and the production network as well as customer orders are taken as input for the Global Order Assignment tool (3). The output of the tool, which is the assignment of orders to sites and periods is used as input for the Local Order Scheduling tool (4).

In order to consider deterministic capacity demand for the task of local order scheduling, respective options have to be specified according to the Just-In-Time Specification tool by then [50]. In the case of mixed-model assembly lines at the production sites, workload deviations can be minimised over all sub-periods of a period, when assigning orders to lines and cycles [52]. As the calculation is quite similar to that of the Global Order Assignment tool, it is not presented here. The difference is that additional calculation is required in order to obtain the workload deviation of each sub-period based on the respective cycles. The output of the Local Order Scheduling tool (4) is thus the assignment of each order to a line and a cycle.

*Local Order Rescheduling*

The visibility of the production status of each order and the identification of potential delays, which is enabled by tool (C), is essential for satisfying customers since they want to be informed about potential delays so that they can plan the product's usage. Additionally, information on potential delays reported by tool (C) can be used by the production planning department as a trigger to apply the Local Order Rescheduling tool (5), so as to check if a better schedule can be found based on the current production status. This may help to reduce or even avoid the potential delays which may lead to a reduction of customer satisfaction and/or economic losses. Since the calculation of the Local Order Rescheduling tool is similar to the previously presented tools (3) and (4), it is not outlined here. The output of the Local Order Rescheduling tool (5) is an updated assignment of each order to a line and a cycle.

## Experimental results in the aeronautics industry

The following case study was conducted in the aeronautics industry with the intention to indicate the applicability of the integrated decision-support model integrating the customer. In particular, the historically grown production and supply network for the final assembly of a passenger aircraft manufacturer for one product family with four product models is considered featuring large product variety. This network includes several first tier part suppliers, as well as a set of four sites, where a total of seven assembly lines operated in the beginning of the planning horizon. In addition to the assembly processes, painting and testing process steps can be performed at every site in designated site segments. The aircraft manufacturer dealt with a customer order backlog of several years for the considered product family.

### *Production Network Design*

For the Production Network Design tool (1), a planning horizon of five years was set owing to the known product portfolio that was developed to meet forecasted customer requirements for that time horizon. Five years are adequate to consider as strategic cycles are becoming shorter and are currently shorter than five years for most companies [53]. The known large-variety product portfolio was grouped into 10 product variant clusters (PVC) using a k-medoids clustering approach of historical customer orders. For the grouping, several variables were used, including the four basic product models, the feasible process sequences of the product variants, and the related workload of the variants at the assembly, paint, and testing segments using existing or potential assembly technologies.

A forecasted best-case scenario for quarterly customer demand for the clustered product variants of the aircraft manufacturer over the aforementioned planning horizon is illustrated in Fig. 7. The figure shows a clear trend in demand increase, with its peak at 160% in the second quarter of year five.

To avoid large capital expenditures, the first step performs a check of whether the initial production network is capable of providing sufficient capacity to meet increasing customer demands. Therefore, the search space is restricted to the utilisation of only the implemented flexibility measures, and does not allow structural reconfigurations. As illustrated by the red line in Fig. 7, the maximum capacity of the initial production network which has utilised implemented flexibility measures to the full extend is outbid at a 12% demand increase. Because an increase of 21% has already been forecasted for the beginning of the second year, there is a clear need to reconfigure the production network early in the five year planning horizon.

To demonstrate the advantage of utilising a mix of flexibility and reconfigurability measures, the results of two models – model (a) and model (b) – of the Production Network Design tool are were compared. In model (a), only reconfigurability measures with respective reconfiguration cost *cR* are implemented; in model (b), both flexibility and reconfigurability measures are put into effect resulting in reconfiguration cost *cR* as well as flexibility cost *cF*.

The results of model (a) and model (b) over the entire planning horizon, are depicted in Fig. 8; when implementing both flexibility and reconfigurability measures (model (b)), the total cost can be reduced by 0.7% in comparison to model (a). This is due to the fact that a mix of flexibility and reconfigurability allows companies to adapt to changes in the most efficient manner. As listed in Table 3, the same process-related reconfigurations are suggested in both models.

In total, 10 new production segments should be opened at already existing sites, and 12 of the initially operating segments should be upgraded to new set-ups of larger capacity. However, in model (a), new segments are partly opened in earlier time periods than in model (b), which results in a lower overall fix cost. This is due to the fact that flexibility measures in model (b) can be utilised to compensate for demand fluctuations up a certain degree.

As hiring and dismissing personnel is the only measure in model (a) that reacts to changes in demand without incurring high investment cost, the frequency of personnel changes is significantly higher in model (a). In contrast, model (b) features various measures, such as overtime, temporary workers, different shift models, and external capacities, to cope with peaks in demand fluctuation. The possibility to choose between a one-shift and a two-shift model is beneficial for two of the existing sites because the workload at these sites is comparably low owing to the high transportation cost. Moreover, fix costs are less expensive for the one-shift operation.

### *Production and Supply Network Monitoring and Redesign*

In parallel, the continuous monitoring of the influencing factors of the production and supply network (tool (2)) is of great importance to secure optimal use of resources and high network performance throughout the planned periods. For this reason, a set of KPIs regarding the production and supply network, including the time, the quality, the cost, and the energy efficiency – which are

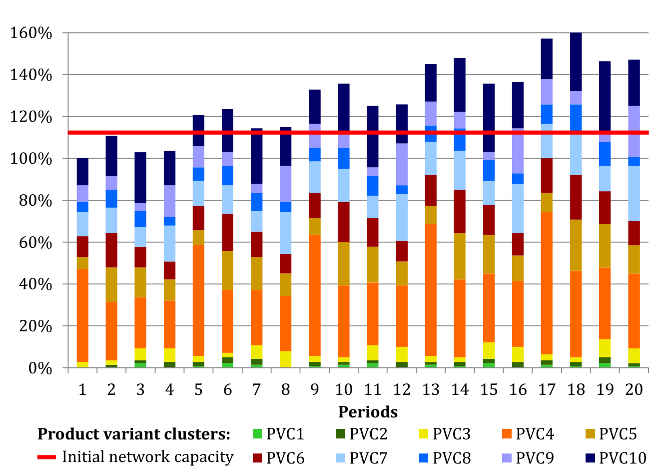


**Fig. 7.** Best-case demand structure for the clustered product portfolio.

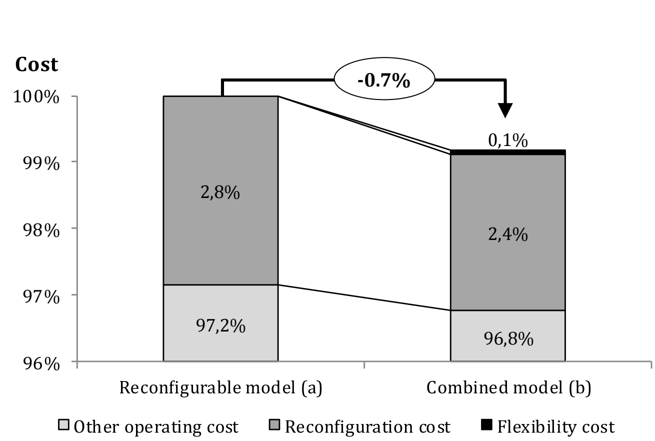


**Fig. 8.** Cost comparison of models (a) and (b) over five years.

**Table 3**
Comparison of production segment openings and technology and resource alterations in models (a) and (b).

| Periods | Reconfigurable model (a) | | | Combined model (b) | | |
|---|---|---|---|---|---|---|
| | Segment openings | Technology alterations | Resource alterations[a] | Segment openings | Technology alterations | Resource alterations[a] |
| 1 | | | | | | |
| 2 | 2 | 6 | 11% | 2 | 6 | 20% |
| 3 | 4 | 4 | 21% | 3 | 4 | 2% |
| 4 | | | −9% | | | |
| 5 | 1 | | −3% | 1 | | 8% |
| 6 | | | 3% | | | 1% |
| 7 | | | 23% | | | 3% |
| 8 | | | −10% | | 2 | |
| 9 | | | −2% | | | 4% |
| 10 | | | 1% | 1 | | |
| 11 | 1 | | 24% | | | 14% |
| 12 | | | −10% | | | |
| 13 | | | −5% | | | |
| 14 | | | 4% | | | |
| 15 | | 2 | 24% | | | 11% |
| 16 | 2 | | −11% | 2 | | −3% |
| 17 | | | −3% | 1 | | 4% |
| 18 | | | 4% | | | |
| 19 | | | 23% | | | 10% |
| 20 | | | −11% | | | |

[a] Percentage refers to the initally available resources.

**Table 4**
Exemplary KPI performance evaluation of designed network per time period.

| Measure | Actual | Target (=100%) | Deviation |
|---|---|---|---|
| Cost (%) | 102 | 100 | 2 |
| Time (%) | 103 | 100 | 3 |
| Quality (%) | 100 | 100 | 0 |
| Logistics (%) | 100 | 100 | 0 |
| Energy (%) | 101 | 100 | 1 |

targeted by industrial experts – is monitored and visualised in an easy-to-perceive manner, as illustrated in the example in Table 4.

Exemplary targeted KPI values were defined by the aircraft manufacturer's industrial experts, as shown in the example of Table 4; they evaluated the performance of the designed network, and supported the decision-making process of both the production and the supply network. The targeted values come from previous experience in combination with the new targets of the manufacturer. In case of a high divergence between the targeted and the actual performance, the production and supply network can be re-designed. The re-design of the network may occur based on the continuous feedback from the customer through the Customer Use Feedback tool (A). In this tool, the preferences of customers are captured which may have a direct influence on the criteria weights. For instance, faster delivery may be highly valued by the customers so improving the time related KPI becomes more important in comparison the remaining KPIs. This may lead to the redesign of the supplier network by adding additional local suppliers.

Finally, as shown in the example in Fig. 9, the availability of suppliers and manufacturing resources is monitored by adjusting and updating the network design; this results in a high-efficiency

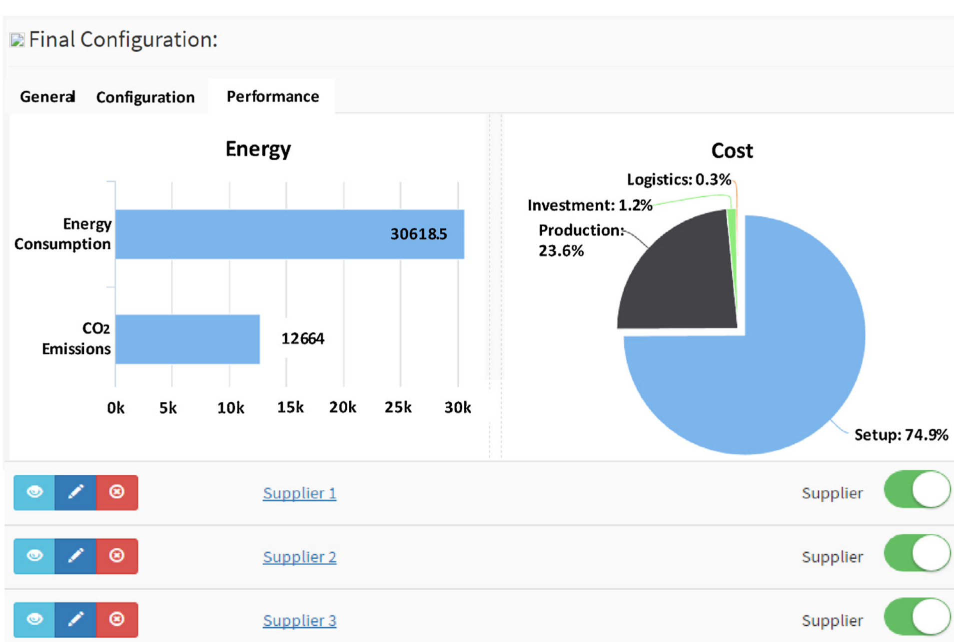


**Fig. 9.** Exemplary KPI and availability monitoring.

network that may rapidly adapt to any supplier and manufacturing shortcomings. The constant performance monitoring of the production and supply network leads to high performance and flexibility. Meaningful information becomes available to the industrial experts; thus, they may detect potential discrepancies in KPI targets, or alterations in resources and supplier availability. This allows quick adaptation of the designed network, by selecting new suppliers and re-allocating operations.

*Global Order Assignment and Local Order Scheduling*

Based on the planning results, in terms of production and supply network structures and capacities, orders can be assigned to assembly sites and periods by the Global Order Assignment tool (3). Therefore, in the present industrial application, customers are asked to select one out of four product models for an order prior to the global order assignment [50]. It is sufficient to confirm quarters of the delivery for most of the customers in the case study; therefore, in the process of global order assignment, orders are assigned to one of the three months of a quarter, apart from assigning them to one of the four sites for assembly [50]. Regarding the month, the shift between the month of starting the assembly and the month of delivery, which is based on the throughput time, cannot be neglected. The number of cycles – and thus the possible production volume – is considered as given for each month at each site, apart from the capacity of each month at each site.

The offer of the Just-In-Time Specification service (tool (B)) causing uncertainty of the selection of options for global order assignment is a regular process in the industrial application compared to irregular requests for late changes of options by customers [50]. Thus, there is an advantage of considering the uncertainty of order specification, i.e. the selection of options, for global order assignment compared to neglecting uncertainty [50].

Both alternative objective functions presented in Section “Decision-support model for customer integration in the design, planning, and control of production networks”, the minimisation of (a) the sum and (b) the maximum of the modulus of the relative workload deviations, have been applied to achieve experimental results. Exemplary data are used for workload and capacity supply. The resulting objective values and workload deviations for each month at each site are listed in Table 5. It states the minimised objective functions, as well as the maximised, to obtain reference values because the maximum may occur in the worst case, when assigning orders randomly.

In the given example, it is revealed that (a) the sum of workload deviations can be reduced from 146.90% to 55.01%, and that (b) the maximum of the workload deviations can be reduced from 18.46% to 8.20%. When examining the maximum value of workload deviations when minimising their sum, it can be observed that the maximum deviation of 10.58% is higher than in the case minimising it being 8.2%. On the other hand, when minimising the maximum of the deviations, the sum of deviations is 72.86% which is quite high compared to 55.01% that can be reached when minimising the sum. Thus, it can be concluded that there is a trade-off between preventing a high deviation for a specific month at a specific site and maintaining the overall deviations at a low level. Moreover, it can be observed from Table 5 that when minimising the sum of workload deviations, (a) the deviations may significantly differentiate between the sites and months. This occurs because the relative calculation of each deviation according to Eq. (6). leads to the shifting of the workload to locations and months of higher capacity; therefore, it leads to a lower relative deviation compared with shifting it to locations and months of low capacity. By minimising workload deviations when assigning orders to sites and months, throughput times of orders in the final assembly can potentially be shortened because additional lead times – otherwise required for handling work overload – are avoided. Based on global order assignment, the workload can be balanced even within the months of production at the individual production sites by the Local Order Scheduling tool.

**Table 5**
Minimisation of the modulus of relative workload deviations.

| Objective function | | a) | | b) | |
|---|---|---|---|---|---|
| Site l | Month t | max | min | max | min |
| 1 | 1 | 16.48% | 3.79% | 5.07% | 8.20% |
| 1 | 2 | 8.43% | 5.01% | 0.56% | 6.39% |
| 1 | 3 | 9.59% | 10.58% | 8.30% | 5.52% |
| 2 | 1 | 9.80% | 2.59% | 10.12% | 4.37% |
| 2 | 2 | 10.53% | 0.01% | 0.63% | 8.16% |
| 2 | 3 | 9.45% | 9.54% | 3.07% | 5.34% |
| 3 | 1 | 10.68% | 7.68% | 9.68% | 7.81% |
| 3 | 2 | 11.05% | 8.37% | 9.55% | 7.85% |
| 3 | 3 | 10.82% | 7.44% | 9.05% | 7.83% |
| 4 | 1 | 16.33% | 0.00% | 11.24% | 3.14% |
| 4 | 2 | 15.43% | 0.00% | 1.32% | 6.96% |
| 4 | 3 | 18.31% | 0.00% | 18.46% | 1.28% |
| sum (all $l$, $t$) | | 146.90% | 55.01% | 87.04% | 72.86% |
| max (all $l$, $t$) | | 18.31% | 10.58% | 18.46% | 8.20% |

*Local Order Rescheduling*

The visibility of the production status enabled by tool (C) is essential for satisfying customers, particularly in the case of aircraft production because the usage of the products has been already timed by the customers. Based on the current production status and respective potential delays, the production planning department can check, whether a better schedule can be found by applying the Local Order Rescheduling tool (5). As the potential for rescheduling in mixed-model lines is limited owing to fixed cycle times, there is potential for rescheduling, specifically in job shops which are prevalent in aircraft production.

## Conclusion

To differentiate themselves from competitors, companies have to consider customer requirements at early production-planning stages and during the order fulfilment process. Simultaneously, they need to manage increased complexity when utilising their global production and supply networks. In the present collaborative work, a decision-support model was introduced, which integrates production network planning and control tools at strategic, tactical, and operational levels meanwhile, the model offers customers the possibility to actively engage in the network design process, the product configuration specification process, and to be well informed about the production status of their order. The advantages of application of the model were revealed through a case study in the aeronautics industry, which underpinned the relevance of such integrated decision-support models. Future work will focus on the further development of the outlined customer involvement tools, the application of the Local Order Scheduling tool (4) and Rescheduling tool (5) and extending the application of the method in more use cases.

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