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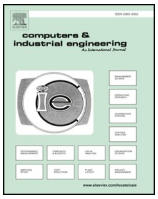

A mathematical model at the detailed design phase in the 3DCE new product development

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ABSTRACT

Recent business environment development forces companies to speed up their new product development (NPD) cycle. The three-dimensional concurrent engineering (3DCE) offers chances to accelerate the process of new product development. However, to date there has been no formal guidelines for 3DCE NPD. This study tries to relate the imperative of concurrency into the stage-gate NPD, especially at the detailed design phase, in which the NPD team is presumed to conduct the decisions on product detailed specifications and production process design simultaneously. A mixed-integer non-linear programming (MINLP) mathematical model was developed to optimize operational manufacturing profit. The main features of the model are to select the best components from available alternative components, to take make-or-buy decision of the components, and to select its suppliers. In addition, the total quality of the components was evaluated and then compared to an expected total quality obtained from the competitors' product or ideal expectation of the NPD team. A case from a leather bag company was used to demonstrate the model. In this case, sixteen components from 24 alternative components and seven suppliers for a new leather bag product case had to be decided and it was solved by the model. The sensitivity analysis provided evidence of model validity. Finally, a conclusion with several potential future works is provided.

1. Introduction

The change in market environment nowadays has forced companies to speed up their ability to create a new product so that it shortens time to market. This environmental change is caused by the increase of customer expectations, e.g. higher quality products, lower prices, better performance, and shorter delivery time (Shidpour, Bernard, & Shahrokhi, 2013). Therefore, companies have been forced to continuously generate new products and at the same time improve product quality and maintain price to win the competition.

In response to this, attention to the new product development approach especially in minimizing product development time by parallelizing all possible activities in NPD has increased. Since 1980 many companies have applied concurrent engineering (CE), where product design and manufacturing processes are typically developed simultaneously (Smith, 1997). A large portion of research then comes under the heading of CE and is proven to be able to decrease time to market and life cycle cost (Eppinger, 1991; Koufteros, Vonderembse, & Doll,

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Abbreviations: NPD, New Production Development; 3DCE, Three-Dimensional Concurrent Engineering; FAT, Focus, Architecture, Technology; MINLP, Mixed-Integer Non-Linear Programming; CE, Concurrent Engineering; MOLP, Multi-Objective Linear Programming; TOPSIS, The Technique for Order Preference by Similarity to Ideal Solution; *SP*, Expected selling price; *PLC*, Product Life Cycle: duration which the new product may have demand from customers; *PC*, Cycle time: the duration for producing a unit of new product, which acquired from total preproduction time and assembly time divided by the number of workers.; *ACjk*, Alternative component *k* for component *j*; *MXjks*, Decision variables indicate that alternative component *k* for component *j* is made at manufacturer and buy its required material from supplier *s*.; *BXjks*, Decision variables indicate that alternative component *k* for component *j* is bought from supplier *s*.; *MPks*, Material price for made alternative component *k* from supplier *s*; *BPks*, Material price for bought alternative component *k* from supplier *s*; *RPPkm*, Preproduction process reference for alternative component *k* requires station or machine *m*; *TPPkm*, Preproduction process time; *WPPkm*, Preproduction process time at station or machine *m* for alternative component *k*; *TAT*, Total Assembly Time for a unit of new product; *WQj*, Component *j* weight respect its contribution to total quality; *AQMks*, Made alternative component *k* quality if its material bought from supplier *s*; *AQBks*, Bought alternative component *k* quality if bought from supplier *s*; SALBP-2, Simple Assembly Line Balancing Problem 2; *NJ*, Number of components in a new product; *NoW*, Number of Workers; *EQ*, Expected Quality; *MRks*, The material for made alternative component *k* can be bought at supplier *s*; *BRks*, The material for bought alternative component *k* can be bought at supplier *s*

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2002; Neascu et al., 2005; Alizon et al., 2007; Luh, Ko, & Ma, 2009; Wang, Chen, Hu, & Huang, 2010; Ulrich & Eppinger, 2015). However, although several publications have discussed supplier selection in CE product development (Huang & Mak, 2000; Balasubramanian, 2001; Shahrokhi, Bernard, & Shidpour, 2011), they have not considered supply chain design or supply chain configuration.

On the other hand, integration on supply chain design into product design without considering process design, called the 2D product-supply chain design, has become the point of interest for several researchers. Wang et al. (2016) urged to optimize the product family architecting in conjunction with supply chain configuration decisions and proposed a mixed integer bi-level programming model to deal with leader–follower game decisions between product family architecting and supply chain configuration. In other study, Chiu and Okudan (2010) addressed supply chain performance after freezing the design of the product and proposed graph theory-based optimization methodology, including a mathematical model to tackle supply chain design during product development.

In 1998, Fine coined the three-dimensional concurrent engineering (3DCE) where the product and process design are considered in conjunction with the supply chain design. In this approach, product design, process design, and supply chain design are conducted simultaneously for minimizing re-design or re-work caused by fundamental tradeoffs of the “three dimensions” (Fine, 1998). This method can reduce product development time, life cycle cost, and optimize other determined functions. In 2005, Fine also proposed a mathematical model using weighted goal-programming to select the best product configuration, assembly design, and supply chain design (Fine, Golany, & Naseraldin, 2005). It is proved that the decision could be made simultaneously through the 3DCE approach.

Subsequently, the following researchers proposed model for 3DCE approach in the product design phase, i.e. Huang, Zhang, and Liang (2005), Shidpour, Bernard, and Shahrokhi (2013), and Shidpour, Shahrokhi, and Bernard (2013). Huang et al. (2005) proposed a model to deal with the integration of the design of supply chain systems, product decisions, manufacturing process decisions, and supply chain decisions. Their focus was on optimizing supply chain configuration given commonality among platform products. Shidpour, Bernard, and Shahrokhi (2013) proposed multi-objective linear programming (MOLP) to address the 3DCE problem in the product, process, and supply chain integrated design. They focused on using decision maker opinions to evaluate the candidate suppliers and critical criteria by considering the lack of information in the early design stages. Shidpour, Shahrokhi, and Bernard (2013) proposed MOLP to select product configuration, assembly process, and suppliers that are integrated in the technique for order preference by similarity to ideal solution (TOPSIS) method.

As an improvement of the aforementioned models, this paper proposes a mathematical model that integrates product design, production design, and supplier selection decisions. This model not only results in the best of new product configuration, production design, and selected supplier but also has the ability to guarantee that the product is competitive enough relative to its competitors. The targeted scores are used to reflect the expected price and quality of the product by normalizing the two goals into a single function.

In terms of production design, the model simultaneously optimizes make-or-buy components decision of the new product and divides production capacity of the new product and the components in the manufacturer. Thus, this model not only simultaneously optimizes the new product configuration, production design, and supplier selection, but also results in the make-or-buy decision of new product components.

There are two reasons for including make-or-buy decision of components in the model. Firstly, make-or-buy decision is frequently needed during the product design and engineering process. Secondly, it brings tremendous impacts on manufacturing planning (Dekkers, 2014). Thus, it is eminent to ensure its effectiveness.

The related research in the area of 3DCE mathematical model and the imperative of concurrency or focus–architecture–technology (FAT) system are discussed in the next two sections. In Sections 4 and 5, the model development process and the detailed formulation of the proposed model are described, while the numerical example and sensitivity analysis are discussed in Sections 6 and 7, respectively. Finally, the conclusion and the potential area for further research are provided in Section 8.

2. Literature review

According to Fine (1998), 3DCE should answer where the most excellent opportunities are, which resource in the chain has the shortest delivery time, or where in the chain the large share of the money will be made in the months and years ahead. Furthermore, Fine also suggested the concurrency between decisions follows the “FAT 3DCE Decision Model” which is regulated to make the decisions. However, there is only a few studies discussing 3DCE mathematical modeling in complete product design, process design, and supply chain design between 1998 and 2017 (Ilhami, Subagyo, & Masruroh, 2018). The four models are presented in detail as follows (see also Table 1).

Fine et al. (2005) proposed a weighted goal-programming modelling approach to address 3DCE problems. They used five conflicting objectives which are fidelity (quality), cost (element purchasing cost, element production cost, and assembly cost), lead-time (delivery time from supplier to manufacturer), partnership (proportion of the number of elements supplied by the designated supplier-partner), and dependency (level of risk as a result of reliance on external suppliers). Their research focus was on the integrality or modularity of the new product.

Huang et al. (2005) developed a mathematical model to quantify the relationship among various design decisions, namely product, manufacturing process, and supply chain decisions. They proved that the approach to the decision development supports for investigating the mutual impacts between product development and supply chain configuration. The objective function of the model was supply chain costs that consist of inventory cost, production cost, procurement cost, and transportation cost.

Shidpour, Bernard, and Shahrokhi (2013) proposed a-group decision-making to address 3DCE problems and MOLP mathematical model. They used the opinions of the decision-makers to determine the weight of the objectives function due to the lack of information in the early design stages. They proposed the costs (purchasing cost, assembly cost, and order cost), time (lead time and assembly time), and average defect rate as the objective functions. The model was able to determine the best configuration of product design, manufacturing process, and supply chain.

Shidpour, Shahrokhi, and Bernard (2013) proposed a MOLP integrated in the TOPSIS method and mixed quantitative and qualitative criteria to determine the best configuration of product design, assembly design, and suppliers. TOPSIS method was used to evaluate the results from the model and conclude the best configuration of a design alternative, assembly process, and suppliers. The model was used several times to create design alternatives which will be evaluated using TOPSIS to select one best configuration. The objective functions of the model were cost, time to market, customer satisfaction, and dependency risk. The qualitative criteria used were functional analysis, ergonomics, aesthetics, and serviceability.

3. The 3DCE imperative of concurrency

In the domain of 3DCE new product development, Fine (1998) suggested the imperative of concurrency to implement 3DCE, which is also known as the FAT system. The imperative of concurrency divides the 3DCE decision making into three domains, which are product

Table 1
Summary of 3DCE mathematical models at the detailed design stage.

No	Researcher	Objective Functions	Decision Variables	Remarks
1	Fine et al. (2005) WGP	(1) fidelity (quality), (2) element purchasing cost, (3) element production cost, and (4) assembly cost, (5) lead-time (delivery time from supplier), (6) partnership (proportion of elements supplied by supplier-partner), and (7) dependency (level of risk)	(1) The binary variable of configuration *j* (2) Binary variable indicates supplier *s* is selected	1. The model's focus on suppliers and manufacturers only. 2. Lead time is not the time to market. 3. No competitor consideration, no guarantee that the selected product will match or above the competitor.
2	Huang et al. (2005)	(1) inventory cost, (2) production cost, (3) procurement cost, and (4) transportation cost	(1) Service time (2) Options selection (entity to produce/order)	1. Pure cost-based model, no other criteria are considered 2. No competitor is considered
3	Shidpour, Bernard, and Shahrokhi (2013)	(1) purchasing cost, (2) assembly cost, (3) order cost, (4) lead time, (5) assembly time, and (6) average defect rate (quality)	(1) Amount of component *j* purchased from supplier *s* (2) Binary var. of component *j* purchased from supplier *s* (3) Binary variable indicates process *i* is selected (4) Binary var. which indicates supplier *s* is selected	1. The model's focus is on suppliers and manufacturers only. 2. Lead time is not the time to market 3. No competitor consideration
4	Shidpour, Shahrokhi, & Bernard (2013)	(1) purchasing cost, (2) assembly cost, (3) investment cost, (4) lead time, (5) customer satisfaction (quality/performance), and (6) dependency risk	(1) Amount of component *i* purchased from supplier *j* (2) Binary variable indicates supplier *s* is selected (3) Binary variable indicates configuration *k* is selected	1. The model's focus on suppliers and manufacturers only.
5	Present model	(1) Total components price (2) Total components quality (3) Total assembly time	(1) The binary index indicates alternative component *k* selected as component *j* and supplied from supplier *s* (2) The binary index indicates alternative component *k* is selected and determines where to produce	Output: (1) Product configuration (2) Supplier selection (3) Production allocation & capacity

architecture – supply chain architecture, detail design – unit processes, and production system – logistic & coordination system (see Fig. 1). The imperative of concurrency is interpreted as product architecture – supply chain architecture, detail product design – process/production design, and production planning – logistic & coordination system.

It is also believed that the FAT system is related to stage-gate new product development. The architecture principle is the product and supply chain architecture design, which is conducted at the conceptual design stage. The technology principle is the detailed product design and process design, which is conducted at the detailed design stage. And the focus principle is the production and supply chain planning, which is conducted at the system level design or testing stage (see Fig. 2). The relation between the FAT system and stage-gate new product development is based on activities in the stage-gate system provided by Ulrich and Eppinger (2015).

The proposed model is a quantitative model for designing detailed product design concurrently with production design at the detailed product design stage. Thus, this model could be called as the Technology Model in terms of the FAT system. Moreover, considering that production capacity is related to how the resources utilized, it is believed that the make-or-buy decision affecting the utilization of the resources (workers) at the manufacturer should be considered. The decision to make components at the manufacturer will require more workers at the manufacturer. Therefore, it will reduce the number of workers allocated to produce the new product. On the contrary, the decision to buy components from component suppliers will increase the number of workers allocated to produce the new product.

4. Model development

Table 1 presents the complete resume of the four models. Based on this table, it can be concluded that the most common objective functions used for the 3DCE mathematical model are (1) quality, (2) purchasing cost, (3) assembly cost/production cost, (4) lead time, (5) order/transportation cost, and (6) dependency. The model developed in this paper accommodates all of those functions except the transportation cost since it should be considered at production and supply chain planning stage (system-level design/testing stage). The consideration of the functions is diverse depending on the context provided.

The purpose of the model is to deal with 3DCE decision making, which are to select components for the new product, to select suppliers, and to design production process by determining its number of workers in order to design production capacity. The model optimizes product quality and operational manufacturing profit. These two functions are normalized by subtracting the functions with their expected profit and quality, respectively. The total quality is the sum of all components' quality configuring the new product; and operational manufacturing profit is revenue subtracted by purchasing cost and production cost.

The model also optimizes operational manufacturing profit, which is obtained from the revenue subtracted by purchasing cost of components and labor cost. Moreover, the total quality of all components configuring the new product is used as a constraint to make sure the components configuration meets the expected quality. As the model is in detailed product design, it requires several inputs from the previous stage, the conceptual development phase in stage-gate development. The conceptual development phase starts with customer needs identification, product concept generation, and creating target specifications (Ulrich & Eppinger, 2015). The main output of the conceptual development phase is product architecture. As per FAT system requirement, new product development team conducts product architecture design simultaneously with supply chain architecture. Here, the product architecture will provide every component needed for the new product; and supply chain architecture will provide targeted market and supplier options for the next stage, the detailed product design stage. Thus, the model will require all selected components for each required function in the product. Then, it will select the components from the available

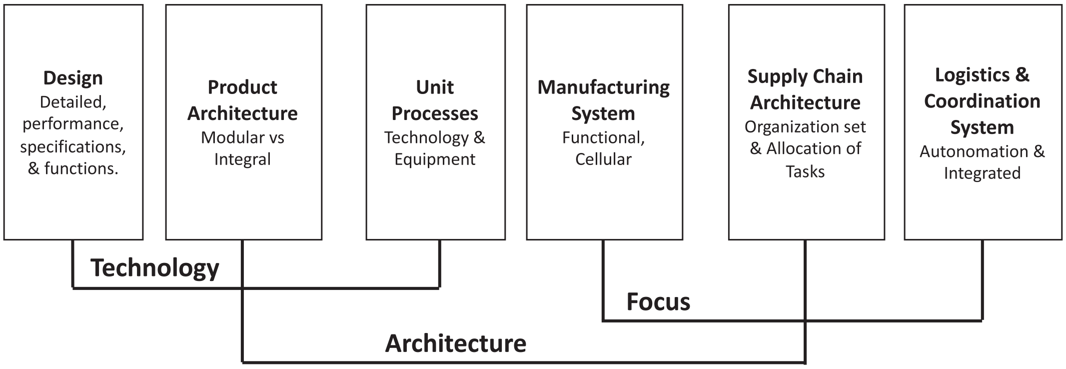

Fig. 1. The imperative of concurrency (the FAT system).

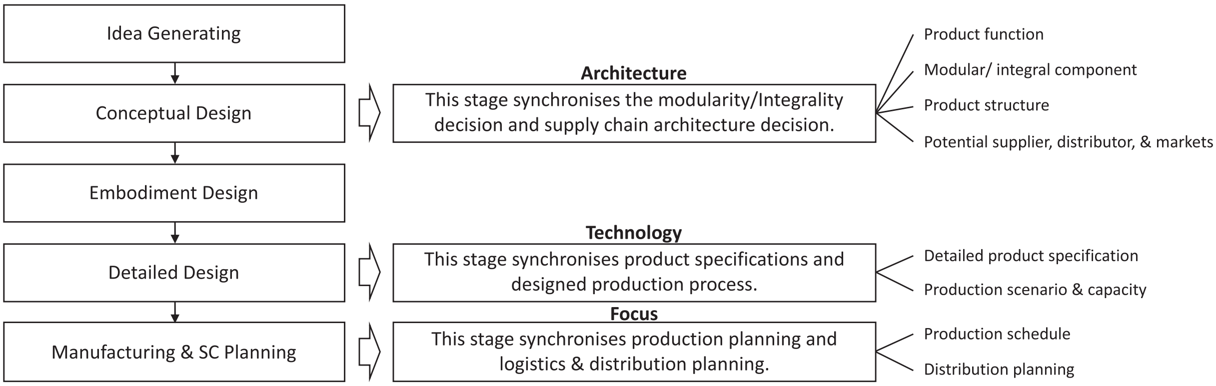

Fig. 2. The FAT system implementation in stage-gate new product development.

alternative components which have the same functions from several alternative suppliers.

Theoretically, it is possible to formulate mathematical model that integrates conceptual development with detailed design, even with manufacturing and supply chain planning. However, since a new product development is not a one-way cycle, it needs feedbacks and options in every stage or phase. Moreover, each stage/phase of development has different level of decision and complexity. As a result, it could create more bias to the result when all three domains considered in each stage.

Fig. 2 shows how the FAT system is synchronous with the stage-gate new product development. The conceptual design stage contains architectural decisions related to product and supply chain architecture. The detailed design stage synchronizes detailed product specification with manufacturing/assembly processes needed. Then, the manufacturing and supply chain planning, including distribution, synchronizes manufacturing schedule/plan with logistics and distribution planning. Ellram, Tate, and Carter, 2007 strengthened 3DCE linkages, especially the linkages between two dimensions, in more detail. The next sub-sections will provide the detailed key functions formulation.

4.1. Revenue

The revenue is formulated as selling price (*SP*) multiplied by product life cycle (*PLC*) and divided by production capacity (*PC*) (see Eq. (1)). Selling price is suggested as a parameter reflecting the competitiveness of the product. Thus, the selling price is set as a constant value estimated from the competitor product price, which can be higher or lower than the competitor. It depends on the product quality justification compared to the competitor. The product life cycle is defined as a duration since a product is available in the market until it finally is disappeared from the market. Moreover, production capacity is a duration for producing one new product, which is determined from total preproduction time and assembly time divided by the number of workers.

$$Revenue = SP\cdot\frac{PLC}{PC} \tag{1}$$

4.2. Purchasing cost

There are two purchasing costs, namely material purchasing cost and component purchasing cost. The material purchasing cost is the cost of purchasing materials for producing components at the manufacturer, while component purchasing cost is the cost of purchasing materials for producing components at the component supplier. The material purchasing cost and component purchasing cost are formulated as in Eqs. (2) and (3).

$$Material\quad purchasing\quad cost = AC_{jk}MX_{jks}MP_{ks}\frac{PLC}{PC} \tag{2}$$

$$Component\quad purchasing\quad cost = AC_{jk}BX_{jks}BP_{ks}\frac{PLC}{PC} \tag{3}$$

where AC_{jk} is an alternative component *k* reference for component *j*, MX_{jks} is the decision to make alternative component *k* as component *j* at the manufacturer and buy its material from supplier *s*, BX_{jks} is the decision to buy alternative component *k* as component *j* and buy it from supplier *s*. While the MP_{ks} and BP_{ks} are the material price for alternative component *k* at supplier *s* and component price for alternative component *k* at supplier *s*, respectively.

4.3. Production/manpower cost

The decision to make components affects preproduction cost since it causes the manufacturer to produce components before they assemble the final product. Thus, the production cost is the sum of preproduction cost and assembly cost. The formulation is determined based on line balancing principle, i.e. the number of workers needed is equal to the total processing time divided by production capacity, while the total processing time is the sum of the preproduction time and assembly time. The production/manpower cost is formulated as the function of preproduction and assembly time multiplied by salary and product life cycle (time) and divided by PC. Eqs. (4) and (5) show the preproduction and assembly time, respectively.

$$The\ \ number\ \ of\ \ component\ \ produced = \frac{RPP_{km}TPP_{km}MX_{jks}}{PC} \tag{4}$$

$$The\ \ number\ \ of\ \ product\ \ produced = \frac{TAT}{PC} \tag{5}$$

where RPP_{km} is preproduction process reference for alternative component k which requires a station or machine m, TPP_{km} is preproduction duration of alternative component k using machine m, and TAT is total assembly time.

4.4. Quality

As mentioned earlier, the quality is proposed to assure that the components configuration meets the expected quality. The quality is formulated as the sum of total quality of bought alternative component and total quality of made alternative component. Eqs. (6) and (7) show the total quality of bought alternative component and the total quality of made alternative component, respectively. Both total qualities are formulated as the multiplication of component weight (WQ_j) respect to its contribution to the total quality, alternative component reference (AC_{jk}), the decision to make-or-buy components (MX_{jks} or BX_{jks}), and bought-or-made alternative component k quality at supplier s (AQM_{ks} or AQB_{ks}). In this case, the analytical hierarchy process (AHP) could provide weight for WQ_j. Moreover, the new product development could use the Likert Scale for determining AQM_{ks} and AQB_{ks}.

The component quality can be measured in generic quantity. The most important thing is what is measured for the quality of the alternative component, used for measuring the quality of the competitor product.

$$Total\ \ quality\ \ of\ \ bought\ \ alternative\ \ component = WQ_jAC_{jk}BX_{jks}AQB_{ks} \tag{6}$$

$$Total\ \ quality\ \ of\ \ made\ \ alternative\ \ component = WQ_jAC_{jk}MX_{jks}AQM_{ks} \tag{7}$$

4.5. The balance of production line

The line balancing purpose is to distribute process/task on a designed level of output on the whole workstations or workers in order to optimize some objectives (Boysen, Fliedner, & Scholl, 2007). In this problem The Simple Assemble Line Balancing Problem 2 (SALBP-2) (Boysen et al., 2007) is used to optimize the cycle time (production capacity) based on the number of workers available.

Based on SALBP-2, the number of workstations can be calculated using the sum production/assembly time divided by cycle time. In this case, the number of workstations is the parameter, while the production/assembly times are state variables. Thus, the cycle time is formulated as the function of total production/assembly time divided by the number of workstations. Moreover, the decision variables are make-or-buy components, which determine the pre-production process required. If there is an increase in the number of made components, then the pre-production process is needed; therefore, there is an increase in the total production/assembly time. Furthermore, if the total production/assembly time increases and the number of workers is constant, the cycle time will increase. The cycle time function is formulated as follows (see Eq. (8)).

$$Cycle\ \ time\ \ (PC) = \frac{Total\ \ Preproduction\ \ Time + Total\ \ Assembly\ \ Time}{Number\ \ of\ \ workers} \tag{8}$$

5. The proposed model

The purpose of the model is to deals with 3DCE decision making that is to select alternative components for the new product, including the make-or-buy decision, supplier selection, and determination of the number of workers based on the preproduction and the assembly process selection. In the model, the decision related to alternative components is important because it determines the opportunity of the product to win the competition. In this case, quality is the only competitive variable considered. The new production team may get the expected scores using a competitor product as the reference. Thus, the new product quality is better than or at least equal to the competitors.

The model maximizes the operational manufacturing profit (total manufacturing revenue – purchasing cost – production cost). The decision variables of the model are the alternative component that represents the selected made-or-bought component, the supplier that provides the component, and the required preproduction processes. In this case, the model employs MINLP (mixed integer nonlinear programming). The proposed model is presented below while the complete notations and definitions are provided in abbreviation section.

Max z = operational manufacturing profit/expected profit + quality/expected quality

$$\begin{aligned} MaxZ &= SP\cdot PLC/PC \\ &- \textstyle\sum_j \sum_k \sum_s (AC_{jk}\cdot MX_{jks}\cdot MP_{ks} + AC_{jk}\cdot BX_{jks}\cdot BP_{ks})\cdot PLC/PC \\ &- \frac{\sum_j \sum_k \sum_s \sum_m RPP_{km}\cdot WPP_{km}\cdot MX_{jks} + TAT}{PC}\cdot PLC\cdot G \end{aligned} \tag{9}$$

$$\sum_j \sum_k \sum_s (WQ_j\cdot AC_{jk}\cdot MX_{jks}\cdot AQM_{ks} + WQ_j\cdot AC_{jk}\cdot BX_{jks}\cdot AQB_{ks}) \geq EQ \tag{10}$$

$$\textstyle\sum_k \sum_s MX_{jks} + \sum_k \sum_s BX_{jks} = 1 \qquad \forall\, j \tag{11}$$

$$PC = \frac{\sum_j \sum_k \sum_s \sum_m RPP_{km}\cdot WPP_{km}\cdot MX_{jks} + TAT}{NoW} \tag{12}$$

$$MX_{jks} \leq AC_{jks}MR_{ks} \qquad \forall\, j, k, s \tag{13}$$

$$BX_{jks} \leq AC_{jks}BR_{ks} \qquad \forall\, j, k, s \tag{14}$$

$$MX_{jks}, BX_{jks} \in \{0, 1\} \qquad \forall\, j, k, s \tag{15}$$

Eq. (9) presents the objective functions of the model that is to show the potential operational manufacturing profit of the new product, i.e. operational revenue subtracted by purchasing and production costs. Eq. (10)–(15) are the constraints of the model. Eq. (10) prevents product quality resulted from the model to be lower than the expected quality. Eq. (11) guarantees only one decision for each component, whether the manufacturer should make or buy the component. Eq. (12) makes sure the relation between production capacity and the made component decision, that is the more components made, the less production capacity for producing the new product. Eqs. (13) and (14) make sure that the decision variables follow the component-alternative component reference (ACjks) and alternative component-supplier reference (MRks or BRks). Finally, Eq. (15) is the binary constraint for the decision variables. By solving the model, the selected components, the make-or-buy decisions, selected suppliers, and required preproduction processes are determined.

In terms of compatibility with the Smart Manufacturing Executing System (SMES), possible information such as processing times and setup times can be acquired directly based on the historical data. Since the SMES aims for leveraging an existing MES is to reduce the cost and environmental impact in manufacturing through reducing cycle times, rework, materials, energy, emissions, wastes and scraps (Larreina et al., 2013), the model can be enriched using the additional SMES criteria such as some environmental and social factors. In addition, the proposed model is very likely to be developed further using other parameters whether design parameters or manufacturing parameters. Product life cycle consideration increases designer responsibility in term of considering “tomorrow” factors, e.g. reuse, further use, reprocessing, further processing, etc. (Niemann & Tichkiewitch, 2008). Using SMES as the source of data, the involvement of more parameters becomes feasible.

6. Numerical example

As mentioned earlier, the model for 3DCE environment is proposed at the detail design phase of the stage-gate new product development. The model will require the product concept, component alternatives, suppliers and the component prices, and production and assembly process needed. It provides several outputs such as detailed specifications of the new product, selected suppliers, and the selected pre-production and assembly processes, which required as outputs at the detailed design phase. Thus, this model is proposed as an additional tool for the 3DCE new product development at the detailed design phase.

The numerical example is presented to demonstrate the model ability in dealing with real problems. In this case, a leather bag company plans to design a new leather sling bag that has 16 components that have to be selected from 24 alternative components having to be ordered from 8 different suppliers. The company also has to decide whether to make or buy these components where this can add or reduce the pre-production process.

In addition, the following parameters are used. The new product life cycle is six months, the expected product price is Rp1,140,000.00, the total assembly time is 135 min/unit, the number of workers available is 30 people, and the production cost is Rp158.73/minute/person. After analyzing the quality of competitors' products, it was established that the expected quality of new products is 90 (out of 100) so that new product could compete with competitors.

Three scenarios were proposed to test the model ability in selecting various alternative component related to product quality targeted. The first scenario, the model was run for a high-end product with expected quality score was 90 at a minimum. The second, the model was run for a medium-end product with the expected quality score was at least 85. The last scenario, the model was run for a low-end product with the expected quality score was at least 80. In order to get a globally optimal solution, LINGO 18.0, one of MINLP solvers, is used to run these scenarios. This is different from most of MINLP solvers that according to Yao and Askin (2019) only give locally optimal solutions for the majority of MINLP problems. Tables 2 and 3 show the comparison of results from the three scenarios.

Table 2 shows how the model relates quality to other variables, namely production cycle time, purchasing costs, and objective functions. The increase in product quality will also increase production cycle time. It can be explained as follows. The made-component quality is better than the bought-component quality so that the quality of product using made-component is better. However, producing more components will result in the increase of production cycle time. Conversely, the decrease of product quality will reduce the number of made component and increase the bought component. This will bring about the increase of the purchasing cost per unit and reduce the total production costs. In terms of objective functions, the decrease in quality will increase objective functions because the expected selling price is the same for all three scenarios.

Table 3
The make-or-buy decision on each component of the three scenario results.

No	Components	High-End	Medium-End	Low-End
1	Outsole Leather	Make	Make	Buy
2	Insole Fabric	Make	Buy	Buy
3	Zipper	Buy	Buy	Buy
4	Bald Head Acc	Buy	Buy	Buy
5	Leaf Head Acc	Buy	Buy	Buy
6	Magnetic Bowl	Buy	Buy	Buy
7	Silver Slide Ring	Buy	Buy	Buy
8	Flat Rivet	Buy	Buy	Buy
9	Black Composition	Make	Buy	Buy
10	Horse Hook Acc	Make	Buy	Buy
11	Button Pads	Make	Buy	Buy
12	Pocket Buttons	Make	Buy	Buy
13	Bulkhead	Make	Buy	Buy
14	Soh 2,5 Cm Black	Make	Make	Make
15	Rit Hook	Make	Buy	Buy
16	Leather Flag	Buy	Buy	Buy

Table 3 shows the comparison of make-or-buy decisions from the three scenarios. There are nine made components and seven bought components for the first scenario. For the second scenario, there are two made components and fourteen bought components. While for the last scenario, there is only one made component and fifteen bought components. It can be shown that the lower the quality of new products, the smaller the number of made components since for lower quality the company does not need to produce the components on its own. Therefore, the company could focus on increasing its production capacity to maximize its operational manufacturing profit.

The numerical examples demonstrate the capability of model to assist make or buy decisions based on expected product quality. This has not been included in the previous models (Fine et al., 2005; Huang et al., 2005; Shidpour, Bernard, & Shahrokhi, 2013; Shidpour, Shahrokhi, & Bernard, 2013). Moreover, these numerical examples show how the model assists to find the best components configuration for each scenario faster. Without the model, the NPD team should create several product configurations and then evaluate for the next stage in new product development.

7. Sensitivity analysis

Sensitivity analysis was conducted for validating the model by changing two critical parameters, i.e expected quality (EQ) and the number of worker (NoW), and then analyzed separately. The sensitivity analysis results are presented in Tables 4 and 5. As predicted, the expected quality affects the objective function, decision variables, cycle time, purchasing cost, and production cost. Meanwhile, the number of workers only affects the cycle time, purchasing cost, and also the objective function.

Based on Table 4, it can be seen that the decrease in expected

Table 2
The complete comparison of the three scenario results.

No	Items Compared	High-End	Medium-End	Low-End
1	Production Capacity (minutes/unit)	6.78	5.45	4.64
2	Quality (of 100)	90.00	85.10	80.25
3	Purchasing Cost (Rp./unit)	392991.00	397091.00	466591.00
4	Production Cost (Rp./unit)	1076.71	864.54	735.97
5	Objective Function (Rp.)	7,965,388,000	9,951,610,000	10,619,800,000

Table 4
The expected quality sensitivity analysis.

Expected Quality (EQ)	Cycle Time (minutes/unit)	Purchasing Cost (Rp./unit)	Production Cost (Rp./unit)	Objective Function (Rp.)	The number of components to make	The number of components to buy
90	6.78	392,991	1077	7,965,388,000	9	7
85	5.45	397,091	865	9,951,610,000	2	14
80	4.64	466,591	736	10,619,800,000	1	15
75	5.31	305,061	843	11,527,270,000	1	15
70	4.50	353,511	714	12,853,020,000	0	16
65	4.50	353,511	714	12,853,020,000	0	16
60	4.50	353,511	714	12,853,020,000	0	16

Table 5
The number of workers sensitivity analysis.

Number of Workers	Cycle Time (minutes/unit)	Purchasing Cost (Rp./unit)	Production Cost (Rp./unit)	Objective Function (Rp.)	The number of components to make	The number of components to buy
10	20.35	392,991	3230	2,655,129,000	9	7
20	10.175	392,991	1615	5,310,259,000	9	7
25	8.14	392,991	1292	6,637,823,000	9	7
30	6.78	392,991	1077	7,965,388,000	9	7
35	5.09	392,991	808	9,292,953,000	9	7
40	5.09	392,991	808	10,620,520,000	9	7
50	4.07	392,991	646	13,275,650,000	9	7

quality will decrease cycle time, purchasing cost, production cost, and the number of made components; conversely, it will increase the objective function and the number of bought components. Thus, the model is valid according to this result. Moreover, Table 5 shows that the number of workers does not affect purchasing cost and the number of made/bought components. This also proves the model validity.

8. Conclusion

The proposed model determines the decision of whether to make or buy components to optimize the operational manufacturing profit obtained from the new product. It shows how the make-or-buy decision could affect the production cycle time in a constant number of workers. Moreover, the sensitivity analysis results show that the expected quality (EQ) is the most influential parameter to the model. Furthermore, the model is proven to be able to generate the make-or-buy decision in selecting the best components, the suppliers, and the number of workers for the pre-production process and the assembly.

For further research, additional parameters for the model, such as supplier dependencies, delivery lead time, and transportation cost, are recommended. Modification into the stochastic environment would be a significant contribution to the 3DCE new product development. Moreover, the model could also be modified into an advanced manufacturing environment such as the 3D printing application.

CRediT authorship contribution statement

Muhammad Adha Ilhami: Conceptualization, Methodology, Software, Validation, Writing - original draft, Funding acquisition. **Subagyo:** Conceptualization, Methodology, Supervision, Validation, Writing - review & editing, Funding acquisition. **Nur Aini Masruroh:** Conceptualization, Methodology, Validation, Project administration, Funding acquisition.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cie.2020.106617.

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