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Integration of part selection, machine loading and machining optimisation decisions for balanced workload in flexible manufacturing system

Mussa I. Mgwatu [a*]

[a] *Department of Mechanical and Industrial Engineering, University of Dar es Salaam, P.O. Box 35131, Dar es Salaam, Tanzania*

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A B S T R A C T

This paper demonstrates the importance of incorporating and solving the machining optimisation problem jointly with part selection and machine loading problems in order to avoid unbalanced workload in the FMS. Unbalanced workload renders to ineffective FMS such that some machines on the manufacturing shop floor become more occupied than others. Since CNC machine tools employed in the FMS are rather expensive, it is mostly important to balance the workload so that all machines can be effectively utilised. Therefore, in this study, two mathematical models are presented and solved in efforts to balance the workload and improve the performance of the FMS. A two-stage sequential approach is adopted whereby the first stage deals with the maximum throughput objective while the second stage deals with the minimum production cost objective. The results show that when part selection, machine loading and machining optimisation problems are jointly solved, more practical decisions can be made and a wide range of balanced workload in the FMS can be realised with minimum production cost objective. The results also show that the available machine time and tooling budget have enormous effects on throughput and production cost.

1. Introduction

Intensive market competition has forced manufacturing industries to focus on flexible manufacturing systems (FMSs). This is because FMSs offer a rapid and timely response to market demands thus helping the manufacturing industries to win competitive advantage. FMSs are highly automated manufacturing systems that consist of a group of processing workstations, usually computer-numerical control (CNC) machine tools, interconnected by automated material handling and storage systems altogether interfaced via a central computer. They are designed to combine the flexibility of a low-production-volume job shop and the efficiency of a high-production-volume flow shop to best suit the batch production of mid-volume and mid-variety of products. Job shop and flow shop are two conventional manufacturing systems that are associated with a traditional arrangement of machine tools on a manufacturing shop floor. In a job-shop system, machines are grouped together to perform similar operations for different parts. In a flow-shop system, machines are arranged together to process the parts as they flow from one machine to the next through the sequence of operations.

Although the installation of FMSs requires a greater capital investment, their expected benefits are substantial. The benefits include increased machine utilisation, less machines, reduced floor space, greater responsiveness to changes, reduced inventories, lower manufacturing lead times, and higher labour productivity. In order to justify these benefits, the FMS resources should be well planned and

* Corresponding author. Tel.: +255 22 2410754, Fax. +255 22 2410114
E-mail: mgwatu@udsm.ac.tz (Mussa I. Mgwatu)

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then effectively utilised to meet the production requirements, achieve the operational objectives and yet provide the payback more quickly. Various FMS planning problems have been addressed at different stages of the FMS's life cycle. Stecke (1985) divided the FMS planning problems into five subproblems of part type selection, machine grouping, machine loading, production ratio, and resource allocation. Hwang (1986) found that among the five planning subproblems, part selection and machine loading are the most important in the FMS. However, the decisions of part selection and machine loading problems in the FMSs may not be effective because they often lead to unbalanced workload. As reported by Liang (1994), some planning policies such as maximising throughput may cause extremely unbalance workloads thereby causing bottleneck in some machines involved in the manufacturing process. The source for unbalanced workload decisions in part selection and machine loading problems may be the fact that the values of machining parameters are always predetermined and not optimised during FMS planning process as exhibited in Liang (1994), Yang and Wu (2002), and Choudhary, et al (2006).

The optimisation of machining parameters such as cutting speed, feed rate, and depth of cut is an essential step in achieving high machining efficiency and effective FMS. Ermer and Kromodihardjo (1981) and Manna and Salodkar (2008) optimised machining parameters for single machine problems while Agapiou (1992) optimised machining parameters for a conventional multi-stage machining system for effective machine utilisation. It is however learnt that previous studies on the optimisation of machining parameters mainly relied on either standalone machines or traditional multi-stage manufacturing systems rather than on FMSs. In order to utilise the machines in the FMS more effectively, it is necessary to determine the optimum machining parameters during the production planning stage. It is the purpose of this study to integrate the decisions of part selection, machine loading and machining optimisation problems in an attempt to balance the workload while improving the performance of the FMS.

2. Theoretical framework

2.1 Mathematical notations

The following mathematical notations are used for providing the theoretical concepts and in formulating the mathematical models for the FMS:

(1) Indices

j index for part type, j=1,..., J

k index for machines, k=1, …, K

o index for operations of part types, o,..., O_j

t index for tool type, t=1,..., T

(2) Decisions variables

x_j = 1, if part type j is selected, 0 otherwise

x_{jotk} = 1, if operation o of part j is processed using tool t on machine k, 0 otherwise

y_{tk} = 1, if tool type t is assigned to machine k, 0 otherwise

v_{jotk} cutting speed for combination j,o, t, k (m/min)

f_{jotk} feed rate for combination j,o, t, k (mm/rev or mm/tooth)

h machine processing time (min)

p_{jk} processing time of part j on machine k (min)

(3) Parameters

α_{jt} tool life constant of the cutting speed for tool t on part j

γ_{jt} tool life constant of the depth of cut for tool t on part j

β_{jt} tool life constant of the feed rate for tool t on part j

λ_{jt} tool life constant of the number of tool teeth in milling operations for tool t on part j

ω_{jt} tool life constant of the tool diameter in milling operations for tool t on part j

δ_{jt} tool life constant of the width of cut in milling operations for tool t on part j

a_{jot} depth of cut for operation o on part j using tool t (mm)

A_k available time at machine k (min)

B available tooling budget ($)

C_e tool cost of machining a single part ($)

C_m machining cost ($)

C_r tool replacement cost ($)

C_t cost per edge of tool t ($)

D_{jot} tool diameter for operation o on part j (mm)

E_{jt} tool life constant for tool t on part j

F^L_{jotk} lower feed rate limit for combination j,o, t, k (mm/rev or mm/tooth)

F^U_{jotk} upper feed rate limit for combination j,o, t, k (mm/rev or mm/tooth)

G_k number of slots on tool magazine of machine k

L_{jo} length of cut for operation o on part j (mm)

M_{jot}, N_{jot} machining constants for operation o on part j using tool t

Q_j production quantity of part type j

q_r number of parts per tool replacement

R_t replacement time for tool t (min)

S_t number of slots required by tool type t

T_{jt} tool life for part j and tool t combination

t_m machining time (min)

t_p processing time of a single part (min)

t_r tool replacement time distributed to each part (min)

u_j value coefficient of part j

V^L_{jotk} lower cutting speed limit for combination j,o, t, k (m/min)

V^U_{jotk} upper cutting speed limit for combination j,o, t, k (m/min)

W_j width of cut on part j (mm)

Z_t number of teeth of tool t

2.2 Theoretical concepts and main assumptions

The concept of solving part selection, machine loading and machining optimisation problems jointly comes with the need to define the relationship among their entities. In reality, processing time and tooling cost form a major linkage among part selection, machine loading and machining optimisation problems. On one hand, the selected parts for processing in the FMS depend on the available machine time. Similarly, due to higher tooling cost, the number of tools that can be loaded on the tool magazine depends on the available tooling budget. On the other hand, machining parameters, processing time and tooling cost are strongly coupled. For instance, at higher cutting speeds, machining time and the related cost are less but more cutting tools are consumed thus increasing tooling cost. Major components of processing time are machining time and tool replacement time.

Machining time is the actual time required to process a part on a machine described as (Narang and Fischer, 1993):

$$t_m = N_{jot} v_{jotk}^{-1} f_{jotk}^{-1} \quad (1)$$

where

$$N_{jot} = \frac{\pi D_{jot} L_{jo}}{1000} \text{, for drilling and tapping/reaming operations, and} \quad (2a)$$

$$N_{jot} = \frac{\pi D_{jot} L_{jo}}{1000 Z_t} \text{ for milling operations.} \quad (2b)$$

Machining cost is the product of machining time and operating cost rate. Denoting U_o as the operating cost rate, the machining cost can be written as:

$$C_m = N_{jot} v_{jotk}^{-1} f_{jotk}^{-1} U_o \quad (3)$$

Tool replacement time is the time needed to remove a worn tool from the machine and replace with a new tool. Tooling cost is the cost of purchasing new cutting tools. Both the tool replacement time and tooling cost are functions of the Taylor's tool life equation. The extended tool life equation reported by Lambert and Walvekar (1978) can be written in the following form:

$$T_{jt} = \frac{E_{jt}}{v_{jotk}^{\alpha_{jt}} f_{jotk}^{\beta_{jt}} a_{jot}^{\gamma_{jt}}} \quad (4)$$

The tool life is reached and the tool can be replaced when several parts have been processed on a machine. It follows that the number of parts at each tool replacement is the ratio of tool life in Eq. (4) to unit machining time in Eq. (1) expressed as:

$$q_r = \frac{E_{jt}}{N_{jot} v_{jotk}^{\alpha_{jt}} f_{jotk}^{\beta_{jt}} a_{jot}^{\gamma_{jt}}} \quad (5)$$

Substituting Eqs. (2a) and (2b) into Eq. (5) and rearranging the terms, the tool replacement time and tooling cost distributed to each part can be respectively presented as:

$$t_r = M_{jot} v_{jotk}^{\alpha_{jt}-1} f_{jotk}^{\beta_{jt}-1} R_t \quad (6)$$

and,

$$C_e = M_{jot} v_{jotk}^{\alpha_{jt}-1} f_{jotk}^{\beta_{jt}-1} C_t \quad (7)$$

M_{jot} is a machining constant which is defined by Wang and Liang (2005) as:

$$M_{jot} = \frac{\pi D_{jot}^{1-\omega_{jt}} L_{jo}}{1000 E_{jt}} \text{ for drilling operations} \tag{8a}$$

and,

$$M_{jot} = \frac{\pi D_{jot}^{1-\omega_{jt}} L_{jo} a_{jot}^{\gamma_{jt}}}{1000 E_{jt}} \text{ for reaming/tapping operations} \tag{8b}$$

The machining constant for milling operations defined by Shnumugam, et al (2002) and Wang and Liang (2005) is:

$$M_{jot} = \frac{\pi D_{jot}^{1-\omega_{jt}} L_{jo} a_{jot}^{\gamma_{jt}} W_j^{\delta_{jt}} Z_t^{\lambda_{jt}-1}}{1000 E_{jt}} \tag{8c}$$

Correspondingly, the tool replacement cost is the product of tool replacement time and operating cost rate and is defined as:

$$C_r = M_{jot} v_{jotk}^{\alpha_{jt}-1} f_{jotk}^{\beta_{jt}-1} R_t U_o \tag{9}$$

Taking the sum of machining time in Eq. (1) and tool replacement time in Eq. (6), the processing time can be represented as:

$$t_p = N_{jot} v_{jotk}^{-1} f_{jotk}^{-1} + M_{jot} v_{jotk}^{\alpha_{jt}-1} f_{jotk}^{\beta_{jt}-1} R_t \tag{10}$$

In similar manner, adding up the machining cost in Eq. (3), tool cost in Eq. (7), and tool replacement cost in Eq. (9), the total production cost can be obtained as:

$$C_p = N_{jot} v_{jotk}^{-1} f_{jotk}^{-1} U_o + M_{jot} v_{jotk}^{\alpha_{jt}-1} f_{jotk}^{\beta_{jt}-1} R_t U_o + M_{jot} v_{jotk}^{\alpha_{jt}-1} f_{jotk}^{\beta_{jt}-1} C_t \tag{11}$$

As shown earlier, both processing time and tooling cost make a significant link among part selection, machine loading and machining optimisation problems. Therefore, Eq. (7), Eq. (10) and Eq. (11) are accordingly useful for the formulation of mathematical models in the subsequent sections. Before formulating the models, the main assumptions are defined as follows:

(1) The manufacturing parameters are deterministic and static. Breakdowns on machines are not considered and parameters are considered as constant and hence do not change over time.
(2) The depths of cut of part-tool-machine combinations are known and given.
(3) The compatibilities of part-machine and tool-part combinations in the FMS are given.
(4) A part type is selected or rejected for processing before the beginning of the production period and remains unchanged during this period.
(5) The CNC machining centres are identical and can perform different operations on any part type. One machining centre can process one operation at a time.
(6) Machining, loading and unloading workstations have sufficient input and output buffer spaces.
(7) Machining centres, raw materials, parts and tools are simultaneously available in the beginning of the production period.
(8) The material handling system, pallets and fixtures are fully available.
(9) Setting-up of parts is performed offline and the times required for transferring parts between machining centres are negligible.

3. Methodology

A theoretical framework in Section 2 provided a relational base of the FMS variables aimed at formulating throughput and production cost models in attempts to integrate the decisions of part selection, machine loading and machining optimisation problems and to achieve balanced workload in the FMS. The model formulation process adopts a two-stage sequential approach as follows. The first stage maximised the throughput of the FMS and the decisions of part selection, machine loading and machining optimisation are simultaneously made. In the second stage, the production cost is minimised while making the decisions of machine loading and machining optimisation but retaining the maximum throughput obtained in the first stage. The two-stage sequential approach was chosen primarily to avoid the complexity of meeting two different objectives concurrently in one aggregate planning problem.

Computational experiments are designed for sensitivity analysis, which involves varying the values of some control factors and examining how the observed results change with variations in control factors. This would help to test out the range of validity of models and data, and also to get more insights of the results and consequently make easier to evaluate and interpret the results. A two-factor full factorial design was adopted with the available machine time and maximum tooling budget as control factors each assigned to 5 levels. Therefore, a total of 5^2=25 computational experiments were conducted using Extended LINGO 11 software. The two FMS models are formulated in the following subsections:

3.1 Maximisation of throughput

The primary objective in the first stage was to maximise the FMS throughput within the boundaries of the operational requirements. The decisions of the integrated part selection, machine loading (operation allocation, part routing and tool assignment) and machining optimisation (cutting speed and feed rate) problem can be obtained when the model is solved. The model for maximising the FMS throughput was formulated by Mgwatu, et al (2009) as follows:

$$\max \sum_{j=1}^{J} Q_j u_j x_j \tag{12}$$

subject to

$$\sum_{t=1}^{T}\sum_{k=1}^{K} x_{jotk} = x_j\,,\ \forall (j, o) \tag{13}$$

$$\sum_{j=1}^{J}\sum_{o=1}^{O_j}\sum_{t=1}^{T} x_{jotk} \geq 1\,,\ \forall k \tag{14}$$

$$\sum_{o=1}^{O_j}\sum_{t=1}^{T} x_{jotk} \leq 1\,,\ \forall (j, k) \tag{15}$$

$$\sum_{j=1}^{J}\sum_{o=1}^{O_j} x_{jotk} \leq y_{tk}\,,\ \forall (t, k) \tag{16}$$

$$\sum_{t=1}^{T} S_t y_{tk} \leq G_k\,,\ \forall k \tag{17}$$

$$\sum_{j=1}^{J}\sum_{o=1}^{O_j}\sum_{t=1}^{T}\left(N_{jot} v_{jotk}^{-1} f_{jotk}^{-1} + M_{jot} v_{jotk}^{\alpha_{jt}-1} f_{jotk}^{\beta_{jt}-1} R_t\right) Q_j x_{jotk} \leq A_k, \forall k \tag{18}$$

$$\sum_{j=1}^{J}\sum_{o=1}^{O_j}\sum_{t=1}^{T}\sum_{k=1}^{K} M_{jot} v_{jotk}^{\alpha_{jt}-1} f_{jotk}^{\beta_{jt}-1} C_t Q_j S_t y_{tk} \leq B \tag{19}$$

$$V_{jotk}^{L} \leq v_{jotk} \leq V_{jotk}^{U}\,,\ \forall (j, o, t, k) \tag{20}$$

$$F_{jotk}^{L} \leq f_{jotk} \leq F_{jotk}^{U}\,,\ \forall (j, o, t, k) \tag{21}$$

$$x_{jotk} = 0 \text{ or } 1,\ \forall (j, o, t, k) \tag{22}$$

$$x_j = 0 \text{ or } 1,\ \forall j \tag{23}$$

$$y_{tk} = 0 \text{ or } 1,\ \forall (t, k) \tag{24}$$

The objective function (12) maximises the FMS throughput where the level of importance of part types at production quantity Q_j can be in terms of dollar or due-date value coefficients u_j. If part type

j is selected, $x_j = 1$, and 0 if otherwise. Constraint (13) states that the total proportion of a part processed at all alternative machines using all feasible tools should be the same for all operations, either $x_{jotk} = 0$ or 1. The variable $x_{jotk} = 1$, if operation o of part j is processed using tool t on machine k, and 0 if otherwise. To ensure that all machines are utilised in the shop floor, constraint (14) binds every machine to perform at least one operation on a part. Constraint (15) prevents recirculation of parts on machines and maintains the flexibility of the system. Constraint (16) ensures that if a part is allocated to a machine, the required tool y_{tk} should be assigned to that machine. If tool type t is assigned to machine k, $y_{tk} = 1$, and 0 if otherwise. Constraint (17) restricts the total number tool types needed on tool slots S_t not to exceed tool magazine capacity G_k. Constraint (18) forces the total processing time at each machine not to exceed the available machine time A_k on the shop floor. Constraint (19) assures that the total tooling cost is not beyond the available tooling budget B. Constraints (20) and (21) give the lower and upper bounds for cutting speed (V^L_{jotk}, V^U_{jotk}) and feed rate (F^L_{jotk}, F^U_{jotk}) respectively. Constraints (22) through (24) represent binary restrictions on the decision variables.

3.2 Minimisation of production cost

The model in the second stage was formulated to minimise the production cost. The selected parts already obtained in the first phase were maintained and used among other input data in the second stage model. There was an attempt to re-assign the selected parts and reallocate the tools to machines, and also to re-optimise the cutting speed and feed rate for the purpose of exploring the most possible minimum production cost. Once the second stage model is solved, the decisions of machine loading (operation allocation, part routing, tool assignment), machining optimisation (cutting speed and feed rate), and processing times of parts on machines can be made. The formulation of the production cost minimisation model is presented as:

$$\min \sum_{j\in J_s}\sum_{o=1}^{O_j}\sum_{t=1}^{T}\sum_{k=1}^{K}\left(N_{jot}v_{jotk}^{-1}f_{jotk}^{-1} + M_{jot}v_{jotk}^{\alpha_{jt}-1}f_{jotk}^{\beta_{jt}-1}R_t\right)U_o Q_j x_{jotk} \tag{25}$$

$$+\sum_{j\in J_s}\sum_{o=1}^{O_j}\sum_{t=1}^{T}\sum_{k=1}^{K} M_{jot}v_{jotk}^{\alpha_{jt}-1}f_{jotk}^{\beta_{jt}-1}C_t Q_j S_t y_{tk} \ , \ J_s = \{j \mid x_j = 1\}$$

subject to

$$\sum_{t=1}^{T}\sum_{k=1}^{K} x_{jotk} = 1, \ j\in J_s, \ \forall o \tag{26}$$

$$\sum_{j\in J_s}\sum_{o=1}^{O_j}\sum_{t=1}^{T} x_{jotk} \geq 1, \ \forall k \tag{27}$$

$$\sum_{o=1}^{O_j}\sum_{t=1}^{T} x_{jotk} \leq 1, \ j\in J_s, \ k \tag{28}$$

$$\sum_{j\in J_s}\sum_{o=1}^{O_j} x_{jotk} \leq y_{tk}, \ \forall(t, k) \tag{29}$$

$$\sum_{j\in J_s}\sum_{o=1}^{O_j}\sum_{t=1}^{T}\left(N_{jot}v_{jotk}^{-1}f_{jotk}^{-1} + M_{jot}v_{jotk}^{\alpha_{jt}-1}f_{jotk}^{\beta_{jt}-1}R_t\right)Q_j x_{jotk} = h, \ \forall k \tag{30}$$

$$h \leq A_k, \ \forall k \tag{31}$$

$$\sum_{o=1}^{O_j}\sum_{t=1}^{T}\left(N_{jot}v_{jotk}^{-1}f_{jotk}^{-1} + M_{jot}v_{jotk}^{\alpha_{jt}-1}f_{jotk}^{\beta_{jt}-1}R_t\right)Q_j x_{jotk} = p_{jk}, \ j\in J_s, \ \forall k \tag{32}$$

$$\sum_{j\in J_s}\sum_{o=1}^{O_j}\sum_{t=1}^{T}\sum_{k=1}^{K} M_{jot}v_{jotk}^{\alpha_{jt}-1}f_{jotk}^{\beta_{jt}-1}C_t Q_j S_t y_{tk} \leq B \tag{33}$$

$$V_{jotk}^{L} \leq v_{jotk} \leq V_{jotk}^{U}, \ j\in J_s, \ \forall(o, t, k) \tag{34}$$

$$F^{L}_{jotk} \le f_{jotk} \le F^{U}_{jotk} \text{ , } j \in J_s, \forall (o, t, k) \quad (35)$$

$$x_{jotk} = 0 \text{ or } 1, j \in J_s, \forall (o, t, k) \quad (36)$$

Constraint (17), $\sum_{t=1}^{T} S_t y_{tk} \le G_k$, $\forall k$, and Constraint (24), $y_{tk} = 0$ or 1, $\forall (t, k)$

The objective function (25) minimises the production cost of the selected parts. Constraints (26)-(29) and Constraints (33)-(36) are equivalent to Constraints (13)-(16) and Constraints (19)-(22), respectively. Constraint (30) assigns equal processing time h at all machines to guarantee balanced workload in the FMS. In Constraint (31), the processing times at machines are bound within the available machine time. Constraint (32) specifies the processing time p_{jk} of each part at different machines.

4. Results and discussions

Both the formulated throughput and production cost models are integer nonlinear programming (INLP) problems and were computed using Extended LINGO 11 software. LINGO is a nonlinear programming software package which has the capability to solve nonlinear programming problems with unlimited number of linear and nonlinear constraints as well as unlimited number of integer, nonlinear and global variables (LINDO Systems Inc., 2008). The computations were conducted using the numerical data summarised in Table 1-Table 5. In the data, the tool-operation and tool-machine compatibilities are pre-specified. Tool life constants were taken from Shnumugam, et al (2002) and Wang and Liang (2005) while the tool costs per edge were obtained from McMaster-Carr Supply Company (2008). Limits of cutting speeds and feed rates were found in Chapman (2002).

Table 1
General industrial data

S/N	Description	Data
1	Number of identical CNC machines	4
2	Tool magazine capacity in number of slots	10
3	Number of slots per each tool type	1-4
4	Operating cost per hour	\$30
5	Tool replacement time	1 min
6	Available machine time	5 days, 24 hours, 3 shifts
7	Estimated maximum tooling budget for a weekly production plan	\$25,000
8	Number of tool types	20
9	Number of part types	10
10	Production quantities for part types 1 through 10 respectively	450, 900, 480, 1300, 2000, 700, 1500, 2500, 1000, 850
11	Value coefficients of part types	1
12	Tool materials	HSS, Carbide
13	Tool availability	100%
14	Part materials	Grey cast iron, carbon steel
15	Raw material availability	100%
16	Operation types	Milling, drilling, reaming, tapping
17	Number of operations on parts	2-3
18	Machining width, length and depth (mm)	Varied
19	Tool sizes (mm) and number of tool teeth	Varied
20	The status of tool life	Computer monitored

Table 2
Tool and empirical data

Part Type	Operation No.	Tool Type	C_t ($)	S_t	α_{jt}	β_{jt}	D_{jot} (mm)	Z_t	γ_{jt}	δ_{jt}	ω_{jt}	λ_{jt}	E_{jt}
	1	1	315	3	3.12	1.09	75	5	0.47	0.62	0.62	0	1.62E+08
		2	325	3	3.12	1.09	90	5	0.47	0.62	0.62	0	1.62E+08
1	2	3	210	1	3.12	1.09	30	4	0.47	0.62	0.62	0	1.62E+08
		4	220	1	3.12	1.09	40	4	0.47	0.62	0.62	0	1.62E+08
	3	5	60	2	2.50	1.25	26	2			1.25		11640
	1	6	40	2	3.03	1.51	25	4	1.51	0.3	1.36	0.3	148880
		7	80	2	3.03	1.51	30	6	1.51	0.3	1.36	0.3	148880
2	2	8	25	4	3.03	1.51	16	4	1.51	0.3	1.36	0.3	148880
		9	35	4	3.03	1.51	20	4	1.51	0.3	1.36	0.3	148880
	3	10	20	1	3.03	1.51	12	2	1.51	0.3	1.36	0.3	148880
	1	1	315	3	3.12	1.09	75	5	0.47	0.62	0.62	0	1.62E+08
		2	325	3	3.12	1.09	90	5	0.47	0.62	0.62	0	1.62E+08
3	2	11	25	1	2.50	1.25	10.2	2			1.25		11640
	3	12	30	1	3.33	1.67	12		0.33		0.67		7774
4	1	6	40	2	3.03	1.51	25	4	1.51	0.3	1.36	0.3	148880
		7	80	2	3.03	1.51	30	6	1.51	0.3	1.36	0.3	148880
	2	13	15	2	3.03	1.51	10	2	1.51	0.3	1.36	0.3	148880
	1	14	90	1	2.50	1.25	38	2			1.25		11640
5	2	15	140	1	3.33	1.67	39		0.33		0.67		7774
6	1	1	315	3	3.12	1.09	75	5	0.47	0.62	0.62	0	1.62E+08
		2	325	3	3.12	1.09	90	5	0.47	0.62	0.62	0	1.62E+08
	2	5	60	2	2.50	1.25	26	2			1.25		11640
	3	16	75	1	3.33	1.67	27		0.33		0.67		7774
	1	8	25	4	3.03	1.51	16	4	1.51	0.3	1.36	0.3	148880
7		9	35	4	3.03	1.51	20	4	1.51	0.3	1.36	0.3	148880
	2	13	15	2	3.03	1.51	10	2	1.51	0.3	1.36	0.3	148880
8	1	17	85	1	2.50	1.25	36	2			1.25		11640
	2	18	160	1	3.33	1.67	39		0.33		0.67		7774
	1	6	40	2	3.03	1.51	25	4	1.51	0.3	1.36	0.3	148880
9		7	80	2	3.03	1.51	30	6	1.51	0.3	1.36	0.3	148880
	2	8	25	4	3.03	1.51	16	4	1.51	0.3	1.36	0.3	148880
		9	35	4	3.03	1.51	20	4	1.51	0.3	1.36	0.3	148880
10	1	19	235	1	3.12	1.09	50	4	0.47	0.62	0.62	0	1.62E+08
		20	245	1	3.12	1.09	60	4	0.47	0.62	0.62	0	1.62E+08
	2	5	60	2	2.50	1.25	26	2			1.25		11640

A set of results for the throughput model including the selected parts, maximum throughput, average workload, number of selected tools for different operations, and the status of the FMS are summarised in Table 6. The results indicate that not all parts and tools were selected for immediate and simultaneous processing on the machines symbolizing that the parts and tools were competing for production resources. The workloads on machines in the FMS were either balanced or unbalanced. For unbalanced workload, some bottleneck machines were identified while others had slack times. The reason for unbalanced workload could be that the parts had different processing requirements including the differences in their machining operations, cutting tools, and machining parameters. However, this study has revealed the fact that, when machining parameters are optimised with part selection and machine loading problems for maximum throughput objective, they are likely to adjust themselves within their allowable limits and in some cases they can provide balanced workloads in the FMS. Furthermore, the magazine tool slots in the machines were not fully utilised even when the workloads in the FMS were balanced. Although machine tool manufacturers normally try to equip machining centres with larger tool magazines in order to reduce the impact of the magazine capacity constraint, larger tool magazines result in higher spindle idle times during tool change-over between different operations. However, lower tool magazine usage results in using fewer cutting tools and thus spending lower total tooling cost. In addition, better tool magazine utilisation requires the tool slots to be loaded as densely as possible. Therefore, the tooling cost and the penalty cost due to unused tool slots can be compromised basing on the economical benefits that suit the needs of a particular FMS.

Table 3
Part and machining data

Part	Operation	Tool	W_j (mm)	L_j (mm)	a_{jot}(mm)	N_{jot}	M_{jot}
1	1	1	68	540	5	25.45	3.15E-07
		2	68	540	5	30.54	3.37E-07
	2	3	26	180	8	4.24	6.36E-08
		4	26	180	8	5.65	7.10E-08
	3	5		32		2.61	3.82E-06
2	1	6	20	600	10	11.78	1.20E-04
		7	20	600	10	9.42	8.44E-05
	2	8	12	105	10	1.32	2.11E-05
		9	12	105	10	1.65	1.95E-05
	3	10	12	80	5	1.51	1.02E-05
3	1	1	68	630	4	29.69	3.31E-07
		2	68	630	4	35.63	3.54E-07
	2	11		45		1.44	6.80E-06
	3	12		45	0.9	1.70	3.99E-05
4	1	6	20	500	8	9.82	7.12E-05
		7	20	500	8	7.85	5.02E-05
	2	13	10	210	6	3.30	3.55E-05
5	1	14		50		5.97	5.44E-06
	2	15		50	0.5	6.13	6.77E-05
6	1	1	68	280	2.5	13.19	1.18E-07
		2	68	280	2.5	15.83	1.26E-07
	2	5		80		6.53	9.56E-06
	3	16		80	0.5	6.79	6.94E-04
7	1	8	12	400	3	5.03	1.31E-05
		9	12	400	3	6.28	1.20E-05
	2	13	10	160	5	2.51	2.06E-05
8	1	17		40		4.52	4.41E-06
	2	18		40	0.75	4.90	4.92E-05
9	1	6	20	420	4	8.25	2.10E-05
		7	20	420	4	6.60	1.48E-05
	2	8	12	360	4	4.52	1.81E-05
		9	12	360	4	5.65	1.67E-05
10	1	19	42	340	3	13.35	1.24E-07
		20	42	340	3	16.02	1.33E-07
	2	5		50		4.08	5.98E-06

Fig. 1 and Fig. 2 give more insights of the results summarised in Table 6 and explore the relationships between tooling budget and throughput, and available machine time and throughput. The observations in these figures show that increasing the tooling budget or available machine time results in increased throughput.

Table 4
Upper and lower limits of cutting speeds

Part	Operation	Tool	V^U_{jot1} (m/min)	V^U_{jot2} (m/min)	V^U_{jot3} (m/min)	V^U_{jot4} (m/min)	V^L_{jot1} (m/min)	V^L_{jot2} (m/min)	V^L_{jot3} (m/min)	V^L_{jot4} (m/min)
1	1	1	152			152	91			91
		2	152			152	91			91
	2	3		152	152			91	91	
		4		152	152			91	91	
	3	5		45	45			12	12	
2	1	6	30			30	9			9
		7	30			30	9			9
	2	8		30	30			9	9	
		9		30	30			9	9	
	3	10		30	30			9	9	
3	1	1	152			152	91			91
		2	152			152	91			91
	2	11		45	45			12	12	
	3	12		19	19			6	6	
4	1	6	30			30	9			9
		7	30			30	9			9
	2	13		30	30			9	9	
5	1	14	45			45	12			12
	2	15	15			15	8			8
6	1	1	152			152	91			91
		2	152			152	91			91
	2	5		45	45			12	12	
	3	16	15			15	8			8
7	1	8		30	30			9	9	
		9		30	30			9	9	
	2	13		30	30			9	9	
8	1	17		45	45			12	12	
	2	18	19			19	6			6
9	1	6	30			30	9			9
		7	30			30	9			9
	2	8		30	30			9	9	
		9		30	30			9	9	
10	1	19	152			152	91			91
		20	152			152	91			91
	2	5		45	45			12	12	

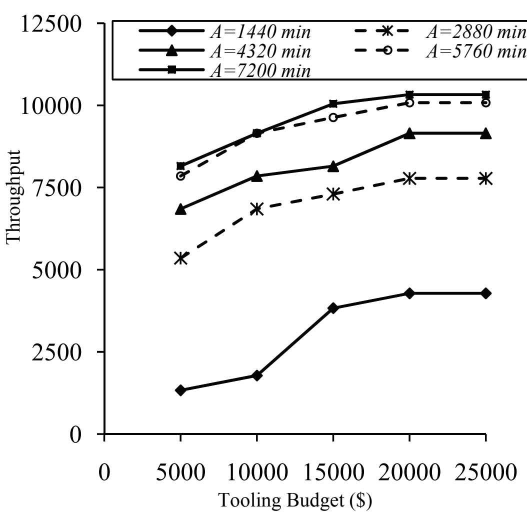

Fig. 1. Relationship between tooling budget and throughput

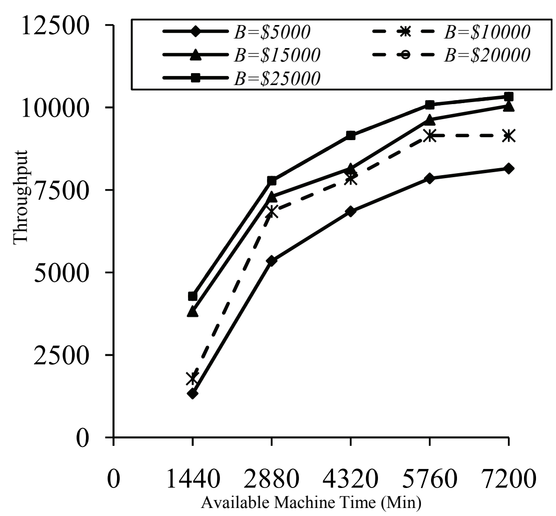

Fig. 2. Relationship between available machine time and throughput

Table 5
Upper and lower limits of feed rates

Part	**Operation**	**Tool**	F^U_{jot1}	F^U_{jot2}	F^U_{jot3}	F^U_{jot4}	F^L_{jot1}	F^L_{jot2}	F^L_{jot3}	F^L_{jot4}
	1	1	0.3			0.3	0.075			0.075
		2	0.3			0.3	0.075			0.075
1	2	3		0.3	0.3			0.075	0.075	
		4		0.3	0.3			0.075	0.075	
	3	5		0.5	0.5			0.23	0.23	
	1	6	0.152			0.152	0.102			0.102
		7	0.152			0.152	0.102			0.102
2	2	8		0.127	0.127			0.063	0.063	
		9		0.127	0.127			0.063	0.063	
	3	10		0.089	0.089			0.038	0.038	
	1	1	0.3			0.3	0.075			0.075
		2	0.3			0.3	0.075			0.075
3	2	11		0.3	0.3			0.13	0.13	
	3	12		0.5	0.5			0.15	0.15	
	1	6	0.152			0.152	0.102			0.102
4		7	0.152			0.152	0.102			0.102
	2	13		0.089	0.089			0.038	0.038	
	1	14	0.5			0.5	0.23			0.23
5	2	15	0.5			0.5	0.25			0.25
6	1	1	0.3			0.3	0.075			0.075
		2	0.3			0.3	0.075			0.075
	2	5		0.5	0.5			0.23	0.23	
	3	16	0.5			0.5	0.25			0.25
	1	8		0.127	0.127			0.063	0.063	
7		9		0.127	0.127			0.063	0.063	
	2	13		0.089	0.089			0.038	0.038	
	1	17		0.5	0.5			0.23	0.23	
8	2	18	0.5			0.5	0.15			0.15
	1	6	0.152			0.152	0.102			0.102
9		7	0.152			0.152	0.102			0.102
	2	8		0.127	0.127			0.063	0.063	
		9		0.127	0.127			0.063	0.063	
10	1	19	0.3			0.3	0.075			0.075
		20	0.3			0.3	0.075			0.075
	2	5		0.5	0.5			0.23	0.23	

Feed rates for milling operations in mm/tooth and other operations in mm/rev.

More results of three representative sets of available machine time and tooling budget for the throughput model are presented in Table 7. As can be seen from the table, the decisions of part selection, machine loading (tool assignment, operation allocation and part routes) and machining optimisation (cutting speeds and feed rates) were simultaneously made while the throughput was maximised. The optimum cutting speeds and feed rates were achieved within their recommended limits.

Table 6
General results for maximum throughput model

Available Time (min)	Tooling Budget ($)	Parts Selected	Maximum Throughput	Average Workload (Min)	Total Tools	FMS Status
1440	5000	3,10	1330	1306.75	8	unbalanced
1440	10000	1,3,10	1780	1413.25	14	unbalanced
1440	15000	3,8,10	3830	1440	10	balanced
1440	20000	1,3,8,10	4280	1440	16	balanced
1440	25000	1,3,8,10	4280	1411.8	16	unbalanced
2880	5000	5,7,9,10	5350	2880	17	balanced
2880	10000	5,7,8,10	6850	2878.15	13	unbalanced
2880	15000	1,5,7,8,10	7300	2880	19	balanced
2880	20000	1,3,5,7,8,10	7780	2880	24	balanced
2880	25000	1,3,5,7,8,10	7780	2877.85	24	unbalanced
4320	5000	5,7,8,10	6850	4320	13	balanced
4320	10000	5,7,8,9,10	7850	4317.95	19	unbalanced
4320	15000	4,5,7,8,10	8150	4320	17	balanced
4320	20000	4,5,7,8,9,10	9150	4317.8	23	unbalanced
4320	25000	4,5,7,8,9,10	9150	4320	23	balanced
5760	5000	5,7,8,9,10	7850	5757.675	19	unbalanced
5760	10000	4,5,7,8,9,10	9150	5760	23	balanced
5760	15000	3,4,5,7,8,9,10	9630	5757.675	28	unbalanced
5760	20000	1,3,4,5,7,8,9,10	10080	5758.3	34	unbalanced
5760	25000	1,3,4,5,7,8,9,10	10080	5760	34	balanced
7200	5000	4,5,7,8,10	8150	7200	17	balanced
7200	10000	4,5,7,8,9,10	9150	7200	23	balanced
7200	15000	2,4,5,7,8,9,10	10050	7198.425	30	unbalanced
7200	20000	3,4,5,6,7,8,9,10	10330	7197.675	34	unbalanced
7200	25000	3,4,5,6,7,8,9,10	10330	7200	34	balanced

Table 7

Decisions of part selection, machine loading and machining optimisation for maximum throughput model

Available Time (min)	Tooling Budget ($)	Part	Operation	Tool	Machine	Cutting Speed (m/min)	Feed Rate (mm/tool or (mm/rev)	Part routes
1440	5000	3	1	1	1	96.1	0.103	M1→M3→M2
			2	11	3	28.6	0.131	
			3	12	2	6	0.150	
		10	1	19	4	103.7	0.076	M4→M3
			2	5	3	12	0.230	
4320	15000	4	1	6	1	28.2	0.133	M1→M2
			2	13	2	30	0.089	
		5	1	14	1	41	0.326	M1→M4
			2	15	4	12	0.500	
		7	1	8	2	28.6	0.098	M2→M3
			2	13	3	30	0.089	
		8	1	17	3	12.1	0.500	M3→M4
			2	18	4	13.6	0.500	
		10	1	20	4	112.3	0.296	M4→M3
			2	5	3	12.1	0.278	
7200	25000	3	1	1	1	91	0.300	M1→M2→M3
			2	11	2	41.3	0.300	
			3	12	3	16.9	0.277	
		4	1	7	4	22.5	0.145	M4→M3
			2	13	3	22.7	0.063	
		5	1	14	4	44	0.320	M4→M1
			2	15	1	14.4	0.351	
		6	1	1	4	91	0.192	M4→M3→M1
			2	5	3	21.8	0.365	
			3	16	1	8	0.311	
		7	1	8	3	30	0.073	M3→M2
			2	13	2	29	0.069	
		8	1	17	2	31.7	0.366	M2→M4
			2	18	4	9.5	0.486	
		9	1	7	1	29	0.127	M1→M2
			2	8	2	19.7	0.063	
		10	1	19	1	91	0.265	M1→M2
			2	5	2	12.1	0.233	

A set of results for the production cost model are summarised in Table 8 covering the minimum cost of the selected part types, average workload, number of selected tools for different operations, status of the FMS, time savings and tool cost savings. The status of the FMS showed that the workloads were fully balanced for all computational experiments. The values of machining parameters indicate changes where cutting speeds are mostly lower and the feed rates are almost higher for minimum production-cost objective in the second stage than for maximum throughput objective in the first stage. Also, slight tool reassignments and significant part reallocation are observed. It has also been shown that operating machines at higher feed rates within their recommended ranges tend to reduce machining time. It is important to note that the time savings indicated might be caused by reduced machining time, and reassigning of tools and reallocation of parts on machines. These observations designate the fact that by re-allocating parts and re-assigning tools on machines, and re-optimising the machining parameters, there is a great possibility of achieving equal processing times amongst the machines and thus balancing the workload in the FMS. Other observations are that, in some cases, the average workload and tool slot usage decreased with time and tool cost savings as compared to those observed in the first stage.

Table 8
General results for minimum production-cost model

Available Time (min)	Tooling Budget ($)	Minimum Cost ($)	Average Workload (min)	Total Tools	FMS Status	Time Saving (min)	Tool Cost Saving ($)
1440	5000	3329.8	524	8	balanced	916	2717.5
1440	10000	8882.8	830	14	balanced	610	2775.5
1440	15000	15223.1	1440	10	Balanced	–	2656.1
1440	20000	20746.3	1440	16	balanced	–	2132.4
1440	25000	20726.2	1440	16	balanced	–	7152.5
2880	5000	10283.5	476	17	balanced	2404	476.1
2880	10000	12067.8	2880	9	balanced	–	3691.8
2880	15000	15223.3	2880	15	balanced	–	5535.6
2880	20000	22694.2	2880	20	balanced	–	3064.2
2880	25000	22701.8	2880	20	balanced	–	8056.6
4320	5000	10910.8	3493	9	balanced	827	1074.5
4320	10000	13959.9	4320	19	balanced	–	4679.7
4320	15000	19050.0	4320	17	balanced	–	4589.7
4320	20000	24496.1	4320	23	balanced	–	4143.2
4320	25000	24496.1	4320	23	balanced	–	9143.2
5760	5000	14165.2	4664	19	balanced	1096	162.0
5760	10000	19699.8	5760	23	balanced	–	1819.9
5760	15000	22625.9	5760	28	balanced	–	3893.2
5760	20000	28731.0	5760	34	balanced	–	2787.6
5760	25000	28820.1	5760	34	balanced	–	7698.4
7200	5000	17092.8	6047	17	balanced	1153	–
7200	10000	19499.0	6403	23	balanced	797	3306.9
7200	15000	25794.7	7200	30	balanced	–	3604.9
7200	20000	30285.2	7200	34	balanced	–	4113.7
7200	25000	29761.5	7200	34	balanced	–	9637.4

The results for the production cost model also uncover the relationships between tooling budget and production cost, and available machine time and production cost which are well depicted in Figure 3 and Figure 4. These figures illustrate the fact that increasing the tooling budget or available machine time brings about an increased production cost. The results of similar representative sets of available machine time and tooling budget for the production cost model are given in Table 9 and Table 10. As can be noted from the two tables, the decisions of machine loading (including tool assignment, operation allocation and part routes), machining optimisation (cutting speeds and feed rates) and part processing times were concurrently made while minimising the production cost. The optimum cutting speeds and feed rates conformed to their recommended lower and upper limits. It is clearly shown that nearly all cutting speeds and feed rates in the second stage are different from those in the first stage. This is again an indication that the cutting speeds and feed rates were adjusted and significantly contributed to the balanced workload in the FMS. The trend of part routes tends to be different comparing to routes obtained in the first stage because of part reallocations in the second stage.

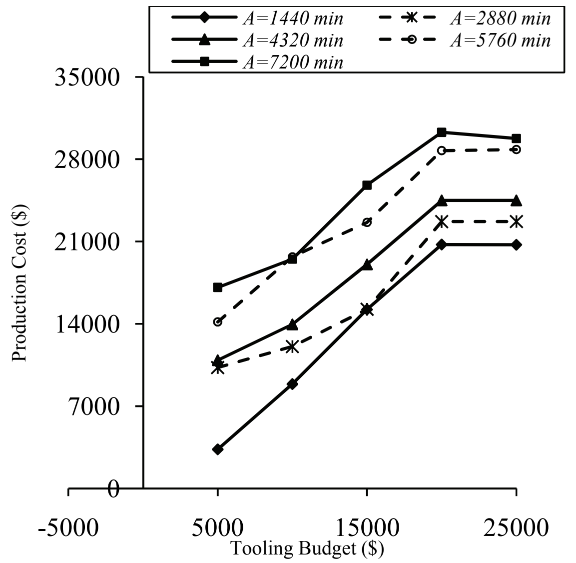

Fig. 3. Relationship between Tooling Budget and Production Cost

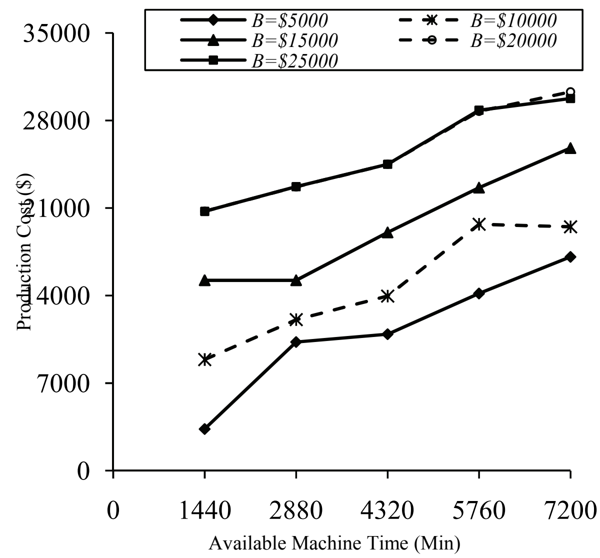

Fig. 4. Relationship between available machine time and production cost

Table 9

Decisions of machine loading and machining optimisation for minimum production-cost model

Available Time (min)	Tooling Budget ($)	Part	Operation	Tool	Machine	Cutting Speed (m/min)	Feed Rate (mm/tool or (mm/rev)
1440	5000	3	1	1	4	91	0.300
			2	11	3	24.4	0.300
			3	12	2	6	0.260
		10	1	19	1	91	0.239
			2	5	3	16.2	0.500
4320	15000	4	1	7	1	20	0.152
			2	13	2	26.5	0.089
		5	1	14	1	45	0.500
			2	15	4	11.5	0.500
		7	1	8	2	23.9	0.127
			2	13	3	16.9	0.089
		8	1	17	3	17.6	0.500
			2	18	4	11.4	0.500
		10	1	19	1	91	0.300
			2	5	3	13	0.500
7200	25000	3	1	1	4	91	0.300
			2	11	2	22.5	0.300
			3	12	3	6	0.500
		4	1	7	1	20	0.152
			2	13	2	17.2	0.089
		5	1	14	4	45	0.500
			2	15	1	8	0.500
		6	1	1	1	91	0.300
			2	5	3	14.2	0.500
			3	16	4	8	0.400
		7	1	8	2	15.5	0.127
			2	13	3	18.1	0.089
		8	1	17	3	19.1	0.500
			2	18	4	7.9	0.500
		9	1	7	4	29	0.152
			2	8	3	12.9	0.127
		10	1	19	1	91	0.300
			2	5	2	14.9	0.500

Table 10
Decisions of part processing time and part routes for minimum production-cost model

Available Time (min)	Tooling Budget ($)	Part	Operation	Tool	Machine	Part Processing Time (min)	Part routes
1440	5000	3	1	1	4	524	M4→M3→M2
			2	11	3	95	
			3	12	2	524	
		10	1	19	1	524	M1→M3
			2	5	3	429	
4320	15000	4	1	7	1	3370	M1→M2
			2	13	2	1829	
		5	1	14	1	533	M1→M4
			2	15	4	2152	
		7	1	8	2	2491	M2→M3
			2	13	3	2505	
		8	1	17	3	1283	M3→M4
			2	18	4	2169	
		10	1	19	1	417	M1→M3
			2	5	3	532	
7200	25000	3	1	1	4	524	M4→M2→M3
			2	11	2	102	
			3	12	3	273	
		4	1	7	1	3368	M1→M2
			2	13	2	2800	
		5	1	14	4	533	M4→M1
			2	15	1	3076	
		6	1	1	1	339	M1→M3→M4
			2	5	3	645	
			3	16	4	1520	
		7	1	8	2	3832	M2→M3
			2	13	3	2342	
		8	1	17	3	1182	M3→M4
			2	18	4	3118	
		9	1	7	4	1505	M4→M3
			2	8	3	2758	
		10	1	19	1	417	M1→M2
			2	5	2	466	

5. Conclusions

In previous studies, the isolation of machining optimisation from the planning of FMSs resulted in unbalanced workload in the FMSs. This study has made an attempt to integrate the decisions of part selection, machine loading and machining optimisation problems for a more balanced workload and therefore effective FMS. Two integrated models have been formulated and solved based on designed computational experiments. The findings illustrate the following two important implications: (i) the maximum throughput objective in the first stage could not guarantee balanced workload in the FMS for the combined part selection, machine loading and machining optimisation problems. Only some cases would demonstrate balanced workloads in this stage; and (ii) the minimum production-cost objective in the second stage guarantees balanced workload in the FMS without affecting the maximum throughput objective in the first stage. With minimised production cost, the bottleneck machines are eliminated and in some cases, the average workloads are decreased. This is a result of re-adjusting the machining parameters such as cutting speeds and feed rates, and also reallocating parts and reassigning tools on machines. The findings also support the applicability of the adopted approach over a wide range of planning period and tooling budget.

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