Model of decision support for the configuration of manufacturing system

Wikarek, Jarosław; Sitek, Paweł; Nielsen, Peter

Published in:
IFAC-PapersOnLine

DOI (link to publication from Publisher):
10.1016/j.ifacol.2019.11.232

Publication date:
2019

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

Citation for published version (APA):
Wikarek, J., Sitek, P., & Nielsen, P. (2019). Model of decision support for the configuration of manufacturing system. *IFAC-PapersOnLine*, *52*(13), 826-831. https://doi.org/10.1016/j.ifacol.2019.11.232

Available online at www.sciencedirect.com
ScienceDirect
IFAC PapersOnLine 52-13 (2019) 826–831

Model of decision support for the configuration of manufacturing system

Jarosław Wikarek*, Paweł Sitek * Peter Nielsen**

** Institute of Management and Control Systems, Kielce University of Technology,*
Al. 1000-lecia PP 7, 25-314 Kielce, Poland, e-mail {j.wikarek, sitek}@tu.kielce.pl).
*** Dept. of Materials and Production, Aalborg University, Aalborg, Denmark peter@mp.aau.dk*

Abstract: Manufacturing enterprises today have to face the volatility of markets, characterized by a decreasing production volume and an increasing number of product variants to meet customer expectations. Traditional dedicated manufacturing lines (DML) have been replaced by flexible manufacturing systems (FMS) and, recently, by the systems that combine features of DML and FMS, i.e., by reconfigurable manufacturing systems (RMS). Appropriate manufacturing support and optimization systems for FMS and RMS will advance the quality and effectiveness of reconfigurable manufacturing. This paper proposes an original mixed integer linear programming (MILP) model for decision support in configuration and reconfiguration of the manufacturing system. The modeled problem is a certain development of the known machine loading problem MLP. In this approach, we generate a highly parameterized model based on a set of constraints and a set of questions. Different mathematical programming (MP) - based solvers are proposed to solve this model.

Keywords: mathematical programming, optimization, decision support, machine loading problem, flexible manufacturing systems, reconfigurable manufacturing systems

1. INTRODUCTION

Manufacturing in general is the transformation of raw materials and components into finished products using different types of resources including main resources (machines, production lines, computers etc.) and additional resources (tools, software, transportation, electricity, workers etc.). The specification and configuration of these resources determines manufacturing system efficiency in terms of time, costs etc. In the past (1970s, 1980s), manufacturing systems included some dedicated machines and tools producing a narrow range of products but in high volumes (economies of scale). This type of manufacturing system is classified as dedicated manufacturing line (DML). Due to rapid changes in customer demand in the decades after 1990, the production objectives changed from high scale of single product production to high customization and responsiveness to changes in the range of products (economies of scope). Flexible machinery, robots, automated guided vehicles; automated storage etc. appeared to form flexible manufacturing systems (FMS), producing mid-volume and mid-variety of products. Limited ability of some FMSs to adapt to changes due to very high costs of production and high cycle time led to a new type of manufacturing system, named reconfigurable manufacturing systems (RMS), developed to compromise both changeable functionality of FMS and scale capacity of DML. In both the FMS and the RMS, operational decisions can be divided into pre- and post-release decisions. Pre-release decisions, also called planning problem, consider the pre-arrangement of tools and parts before the system begins to process. Post-release decisions, also called scheduling problem, deal with the sequencing and routing of parts, when the system is in operation. Among pre-release decisions, the manufacturing system configuration problem, often assimilated to the known machine loading problem (MLP), is considered the most important planning problem with a significant effect on the system performance, especially if we are dealing with multimodal processes (Bocewicz et al. 2015) that require multiple changeovers. This problem comprises a set of sub-problems such as resource allocation, machine grouping, part type selection, production rate determination, and loading. As considering all these problems in a single mathematical model leads to a complex model with many decision variables and constraints, and because the solution is difficult to obtain within acceptable time, models and solution approaches have been developed for each sub-problem separately. In addition, the reliability problem can still be considered (Gola 2019).

Our approach is quite different. We propose an approach which integrates most of the sub-problems in one model but reduces the complexity of the model by introducing a strongly parameterized set of constraints, common for all sub-problems. Adequate selection of these parameters determines the sub-problem areas solved. This obviates the need to build separate models for individual areas. The ways of satisfying the constraints are defined in a set of questions, the answers to which provide decision support for the system configuration problem. The set of questions can be extended for the same set of constraints.

This paper is organized as follows: Section 2 reviews some research in the field of system configuration including MLP. Section 3 describes in details presented problem. A mathematical model for decision support in configuration system problem is formulated. Section 4 presents a number of computational experiments. Section 5 includes conclusion and future works.

10.1016/j.ifacol.2019.11.232

2. LITERATURE REVIEW

The machine loading problem (MLP) plays a leading role in manufacturing system configuration (Abazari et al 2012).. Sarin and Chen (1987) divided MLP into five sub-problems: (a) resource allocation, (b) part type selection, (c) production rate determination, (d) machine grouping, and (e) loading. From the manager's point of view, several objectives may be affected by the solution of MLP. For example, six objectives were defined for FMS (Stecke 1983; Abazari et al 2012). These are balancing the machine processing time, minimizing the number of movements, balancing the workload per machine, maximizing the sum of priorities of operations, unbalancing the workload per machine, filling the tool magazines as densely as possible. The MLP considering two objectives, namely balancing workload and minimizing work stations visits has been modeled and solved by Ammons, Lofgren, and McGinnis (1985). Both approaches use mathematical programming models and methods. The operational problems of flexible manufacturing systems through simulation methods have been investigated and evaluated with different combinations of scheduling rules by a fuzzy integrated DSS by Kazerooni, Chan, and Abhary (1997). To evaluate the performance of a flexible manufacturing system in terms of average flow time, average delay time, and makespan at local buffers, subject to different control strategies which include dispatching rules and routing flexibilities a simulated study has been presented by (Chan and Chan 2004). The swarm optimization approach to solve the MLP in a random flexible manufacturing system with the objective function of minimization of system unbalance was proposed by Biswas and Mahapatra (2007). The MLP has been formulated as a bi-criterion problem (minimization of system unbalance and maximization of system throughput) by Yogeswaran, Ponnambalam, and Tiwari (2007)). This model has been solved using a hybrid genetic algorithm and simulated annealing. The MLP problem treated as the machine-tool operation allocation with the objective goal to determine the optimal machine tool set and the assignment of the available machines to operations while maintaining the setup cost and machining cost within certain limits has been developed by (Chan and Swarnkar 2006). A fuzzy goal programming and ant colony approach to modeling and solving this problem has been used.

As shown in this brief review, MLP has been the subject of research for years, with different methods used, both exact and approximate. Numerous models have been developed, most of which are mathematical programming models (MILP – Mixed Integer Programing, IP – Integer programming). Nevertheless, the majority of the models respond to a single decision question, which is also the objective function of the model.

3. PROBLEM DESCRIPTION

The manufacturing system configuration problem is defined as follows. The production system is composed of a set of main resources -in short resources (machines, production lines, computers, etc.) $E=\{e_1, e_2,\dots,e_k,\dots,e_{LE}\}$ where LE – the number of resources. The system can perform a specified set of tasks/jobs (types of products) $P=\{p_1, p_2,\dots,p_i,\dots,p_{LP}\}$ where LP – the number of tasks. Coefficient $bz_{i,k}=1$ means that the resource $e_k \in E$ can be used to execute task of type $p_i \in P$, otherwise $bz_{i,k}=0$. There are also the following optional parameters: $cz_{i,k}$ the execution cost of task $p_i \in P$ by resource $e_k \in E$, $lz_{i,k}$ the execution time of task $p_i \in P$ by resource $e_k \in E$. The system comprises also additional resources (tools, software, transportation, electricity, workers etc.) $W=\{w_1, w_2,\dots,w_j,\dots,w_{LW}\}$ where LW – the number of additional resource types. These additional resources are limited and uz_w denotes how many additional options w_j are available (e.g. 4 turning tools, 7 drill bits 3 mm, 4 C# software licenses, etc.). Coefficient $az_{i,k,j}=1$ means that additional resource $w_j \in W$ is necessary for the task (type of product) $p_i \in P$ to be executed by resource $e_k \in E$. Each resource $e_k \in E$ has a specified storage/buffer/memory for additional resources and coefficient dz_k specifies how many additional options this storage holds, and oz_k means replacement cost of the storage/buffer/memory. Each resource $e_k \in E$ is required to be used for not longer than wz_k. (as results from, e.g., the maximum number of overtime hours, operating time of a machine, order execution deadline) and for not less than sz_k.

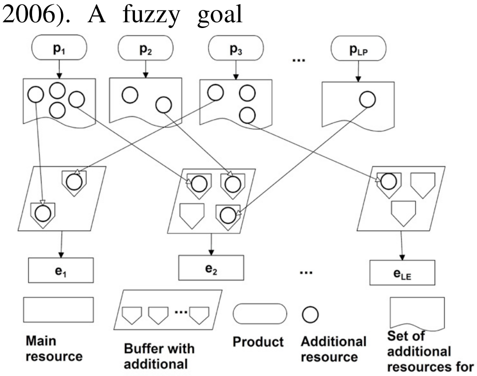

Fig. 1. Manufacturing system configuration for automated press line.

Figure 1 shows an illustrative example of the manufacturing system configuration for the automated press line. Product types $p_1, p_2,\dots p_{LP}$, are to be manufactured. For example, p_1 – the left door (4 stamping dies are available), p_2 – the right door (2 stamping dies are available), p_3 – the front bumper (3 stamping dies are available) etc. Resources e_1, e_2, e_{LE}, are used – these can be the machines, working stations, machining centers, etc. For this example, e_1 – 800kN press machine PN1 (has a storage for 2 additional resources), e_2 – 800kN press machine PN2 (has a storage for 4 additional resources), e_{LE} –1200kN press machine PLE (has a storage for 3 additional resources), etc. Figure 1 shows an example configuration of manufacturing the products on machines. In this configuration, product p_1 can be manufactured only on machines e_1, e_2 (adequate additional resources are mounted in the storage of the machines), product p_2 can be manufactured only on machine e_2, product p_3 can be manufactured only on machines e_1, e_{LE} etc. Machine e_1 is set up for manufacturing products p_1, p_3, the storage is full; machine e_2 is set up for manufacturing products p_1, p_2, p_{LP}, with one free space in the storage, etc.

4. FORMALIZATION AND MATHEMATICAL MODEL

Architecture of the proposed approach is shown in Figure 2. Our model was built on the basis of a set of constraints (1)…(8) and a set of questions Q1..Q5 as a MILP model (Schrijver 1998). The set of constraints was strongly parameterized to enhance the versatility of the model and allow integration of many different sub-problems into one model (loading, resource allocation, part type selection etc.). The choice of questions determines the decisions that are supported by the model and affects how the constraints are satisfied. The set of questions can be supplemented at the basic set of constraints maintained. The detailed description of the questions (D), their formalization (F) and the answers for questions /decisions/ (A) are presented in Table 3. Parameters, indices, decision variables of the model are presented in Table 2 with the description of constraints in Table 1.

Table 1. Description of constraints

Constraint	Description
1	Ensures that all tasks/product types are executed.
2	Ensures that the maximum time of use of a resource is not exceeded.
3	Ensures minimal load on each resource.
4a	Forces adequate setup of a resource for execution of a given task/product type.
4b	Optional – if resource does not execute a task/product, it cannot be setup for its execution.
5	Ensured that the storage is setup with the number of additional resources that does not exceed its capacity.
6	Specifies the maximum number of the additional resources of a given type used.
7	Binarity and integrity.

Table 2. Sets, indices, parameters and decision variables

Symbol	Definition
	Sets
P	A set of task/product types
E	A set of resources types
W	A set of additional resources types
	Indices
i	Index of task/product type $i \in P$
k	Index of the type of resource $k \in E$
j	Index of the type of additional resource $j \in W$
	Parameters
hz_i	How many task/product type i, $i \in P$ needs to be executed
kz_i	Penalty for non-execution of task/product type i, $i \in P$
dz_k	How many items of additional resources can be fixed in the storage of resource k ,$k \in E$
sz_k	Minimum time usage of resource k, $k \in E$
wz_k	Maximum time usage of resource k, $k \in E$
oz_k	Replacement cost of storage of resource k $k \in E$
uz_j	Number of items of additional resource type j, $j \in W$
$bz_{i,k}$	If task/product type i can be executed by resource k, then $bz_{i,k}=1$, otherwise $bz_{i,k}=0$ $i \in P$, $k \in E$
$cz_{i,k}$	Execution cost of task/product type i by resource k $i \in P$, $k \in E$:$b_{i,k}=1$,
$lz_{i,k}$	Execution time of task/product type i by resource k $i \in P$, $k \in E$:$b_{i,k}=1$
$az_{i,k,j}$	If additional resource type j is needed for the execution of task/product type i by a resource k, then $az_{i,k,j}=1$, otherwise $az_{i,k,j}=0$ $i \in P$, $k \in E$, $j \in W$
$gz_{i,k}$	If resource k has been setup for execution of task/product type i, $gz_{i,k}=1$, otherwise $gz_{i,k}=0$, $i \in P$, $k \in E$
st	Arbitrarily large constant
	Decision variables
$X_{i,k}$	Number of tasks/products type i executed by resource k $i \in P$, $k \in E$
$Y_{i,k}$	If resource k has not been setup for execution of task/product type i and is to execute it, then $Y_{i,k}=1$, otherwise $Y_{i,k}=0$ $i \in P$, $k \in E$
$Zc_{i,k}$	If resource k has been setup for execution of task/product type i and is to execute it, then $Zc_{i,k}=1$, otherwise $Zc_{i,k}=0$ $i \in P$, $k \in E$

$$\sum_{k \in E} bz_{i,k} \cdot X_{i,k} = hz_i \forall i \in P \quad (1)$$

$$\sum_{i \in P} lz_{i,k} \cdot X_{i,k} \le wz_k \forall k \in E \quad (2)$$

$$\sum_{i \in P} lz_{i,k} \cdot X_{i,k} \ge sz_k \forall k \in E \quad (3)$$

$$X_{i,k} \le (gz_{i,k} + Y_{i,k} - Zc_{i,k}) \cdot ST \forall i \in P, k \in E \quad (4a)$$

$$X_{i,k} \ge (gz_{i,k} + Y_{i,k} - Zc_{i,k}) \forall i \in P, k \in E \quad (4b)$$

$$\sum_{i \in P} \sum_{j \in W} az_{i,k,j} \cdot (gz_{i,k} + Y_{i,k} - Z_{i,k}) \le d_k \forall k \in E \quad (5)$$

$$\sum_{i \in P} \sum_{k \in E} az_{i,k,j} \cdot (gz_{i,k} + Y_{i,k} - Z_{i,k}) \le uz_j \forall j \in W \quad (6)$$

$$X_{i,k} \in C^{+} \forall i \in P, k \in E \quad (7)$$

$$Y_{i,k}, Z_{i,k} \in \{0,1\} \forall i \in P, k \in E \quad (8)$$

Table 3. Description of questions

Question		Description and formalization
Q_1	D	What is the configuration of the system (setup), i.e., the allocation of additional resources to the main resources, to guarantee the performance of the set of task *hz*?
	F	Constraints (1)..(8)
	A	$Y_{i,k}$
Q_{1a}	D	What is the task allocation to resources for given system configuration?
	F	Constraints (1)..(8)
	A	$X_{i,k}$
Q_2	Q	What is the optimal system configuration (setup), i.e., allocation of additional resources to the main resources, to guarantee the performance of the set of task *hz* with the use of the minimum number of resources?
	F	Constraints (1)..(11), Objective function (12) F_k- If resource k requires changeover than F_k=1, otherwise F_k=0
		$\sum_{i \in P} Zc_{i,k} + Y_{i,k} \le st \cdot F_k \forall k \in E$ (10) $F_k \in \{0,1\} \forall k \in E$ (11) $\min \sum_{k \in E} F_k$ (12)
	A	$Y_{i,k}$
Q_{2a}	D	What is the task allocation to the resources for optimal configuration of the system?
	F	Constraints (1)..(11), Objective function (12)
	A	$X_{i,k}$
Q_3	D	What is the minimum number of system changeovers (storage replacements/additional resource changes) for the performance of the new set of task *hz*?
	F	Constraints (1)..(8)
	A	$Y_{i,k}$
Q_4	D	Can set of task *hz* be performed at *N%* use of resources and what is the system configuration then?
	F	Constraints (1), (3)..(8) and $\sum_{i \in P} lz_{i,k} \cdot X_{i,k} \le N \cdot wz_k \forall k \in E$ (2)
	A	Yes/No
Q_5	D	Can set of task *hz* be performed when resources from set *D* are unavailable and what is the system configuration then?
	F	Constraints (1)..(8)
	A	Yes/No and $Y_{i,k}$

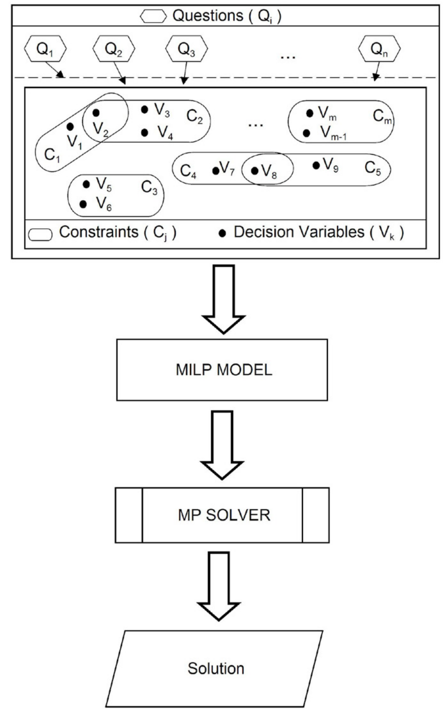

Fig. 2. Architecture of the proposed approach.

5. NUMERICAL EXPERIMENTS

A simple illustrative example was used for calculations, for which the model is one of the possible versions of the model discussed in section 3. In addition to verifying the model, the ease of simplifying the model to individual sub-problems was shown. The problem of production variants configuration was selected, i.e., the way of setting up machines to accomplish a specific set of tasks, so as not to exceed the permissible capacity/load of resources. It was assumed that all the main resources (machines) in the system were identical. For example, we have a set *E* of the same CNC machines on which to perform specific tasks *P* (products, e.g., 10 gear wheels, 15 sleeves, and 20 rings, etc.). Dedicated additional resources (tools) are needed to complete each task. The number of pieces of each tool is limited and is equal to uz_j. This configuration problem is formalized by proper parameterization of constraints. Machine versatility is ensured by setting the coefficient $bz_{i,k}=1$ for $i \in P$, $k \in E$. It is assumed that each task type (product) has a specified additional resource (a drill tool, for example) necessary for its execution. This is done by assigning the corresponding values of $az_{i,k,j}$ ($az_{i,k,j}=1$ for $i=j$, $i \in P$, $k \in E, j \in W$ and $az_{i,k,j}=0$ for $i \neq j$ $i \in P$, $k \in E, j \in W$). Ensuring the upper limit of machine running time is setting parameter wz_k. Each machine can only execute a certain number of task types at the given setup (the size of the machine's accessory storage), determined by the adequate value of parameter dz_k. The values of coefficients $hz_i=A$, $hz_i=B$, $hz_i=C$ determine the number of given product items to be manufactured. The number of machines on which the given product can be executed at the same time is determined by the value of the parameter u_j. Values of other parameters are zeroed. Table 4, 5 summarizes the data used in the numerical experiments. The questions used in the computational experiments are provided in Table 6. The obtained results are compiled in Table 7, Fig. 3 Fig. 4 and Fig. 5.

Table 4. Data for numerical experiments part I

i	l_i	hz_i			u_j	i	l_i	hz_i			u_j
		A	B	C				A	B	C	
1	4	5	140	20	4	36	7	20	6	-	3
2	3	4	13	10	4	37	2	2	5	-	3
3	4	5	18	30	4	38	5	2	20	-	2
4	5	4	3	30	4	39	8	3	20	-	2
5	6	3	2	30	4	40	5	4	20	-	2
6	4	6	6	20	3	41	4	5	4	-	2
7	3	7	8	20	3	42	5	7	6	-	3
8	5	3	4	30	3	43	6	8	4	-	3
9	7	5	8	50	3	44	4	9	20	-	3
10	8	8	6	20	3	45	6	8	4	-	3
11	7	3	3	30	3	46	7	7	6	-	3
12	9	2	5	10	2	47	5	6	8	-	3
13	2	6	6	10	2	48	3	9	9	-	2
14	3	8	5	10	2	49	6	7	9	-	4
15	4	4	7	10	2	50	5	6	2	-	4
16	5	8	3	10	3	51	3	5	4	-	4
17	6	6	5	10	3	52	6	4	5	-	3
18	7	3	2	10	3	53	4	6	8	-	3
19	8	5	4	20	3	54	3	8	6	-	3
20	9	6	5	30	3	55	6	9	4	-	4
21	4	5	6	-	2	56	3	9	3	-	4
22	3	7	20	-	2	57	4	2	7	-	3
23	5	3	2	-	2	58	5	4	8	-	3
24	4	5	2	-	2	59	4	5	5	-	2
25	6	2	3	-	3	60	3	8	7	-	2
26	7	4	4	-	3	61	6	6	5	-	2
27	4	5	5	-	3	62	5	4	4	-	2
28	6	6	7	-	3	63	4	3	5	-	3
29	8	20	8	-	3	64	5	7	5	-	3
30	9	20	9	-	3	65	4	8	4	-	3
31	2	20	8	-	3	66	3	5	5	-	3
32	3	4	7	-	4	67	3	7	4	-	3
33	4	6	6	-	4	68	7	5	3	-	2
34	5	4	9	-	4	69	8	4	6	-	2
35	6	20	7	-	4	70	9	5	7	-	2

A – value of parameter hz_i for N1,N2,N6,N7
B – value of parameter hz_i for N3
C – value of parameter hz_i for N4,N5

Table 5. Data for numerical experiments part II

k	wz_k	dz_k	k	wz_k	dz_k	k	wz_k	dz_k
1	200	5	8	200	5	15	200	4
2	200	5	9	200	5	16	200	4
3	200	5	10	200	5	17	200	4
4	200	5	11	200	4	18	200	4
5	200	5	12	200	4	19	200	4
6	200	5	13	200	4	20	200	4
7	200	5	14	200				

Table 6. Questions for numerical experiments

N	Question	Parameters
N1	Q1	hzi=A
N2	Q2	hzi=A
N3	Q3	hzi=B previous hzi=A
N4	Q1	hzi=C
N5	Q2	hzi=C
N6	Q4	hzi=A, N%=20%,30%,40%,50% How many machines (K) are setup?
N7	Q5	hzi=A, D={1,4,5,7,9}, D={4,15,18}, D={5,15,18}

The sets hz_i=A and hz_i=B contain many different products (80) but in small batches; the set hz_i=C contains small different products (20) but in large batches.

Table 7. Results (Fc-how many machines has been setup)

N	V	C	Lingo		Scip		Gurobi	
			Fc	T	Fc	T	Fc	T
N1	2800	1601	20	45	20	36	20	1
N2	2820	1623	16*	900**	16*	900**	16	3
N3	2800	1601	3	234	3	87	3	5
N4	820	521	19	10	17	8	18	1
N5	840	542	14	2	14	1	14	1
N	Parameter				Answer			
N6	N=20%				YES (K=18)			
	N=30%				YES (K=18)			
	N=40%				YES (K=20)			
	N=50%				NO			
N7	D={1,4,5,7,9}				NO			
	D={4,15,18}				NO			
	D={5,15,18}				YES			

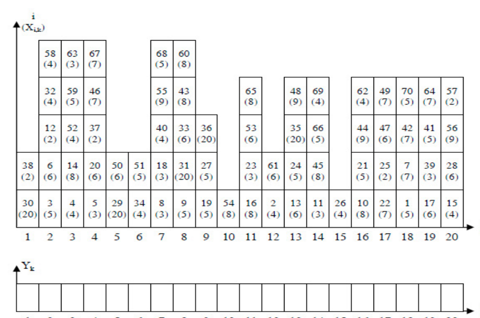

Fig. 3. Results for N1(machines setups and allocation of batch $X_{i,k}$ of product i to machine Y_k).

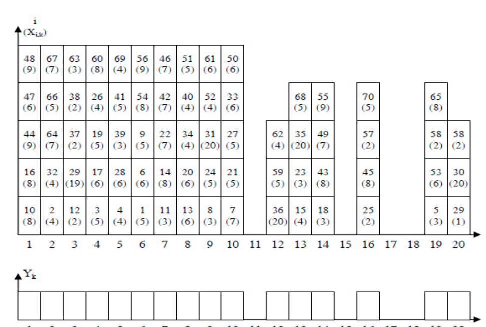

Fig 4 Results for N2(machines setups and allocation of batch $X_{i,k}$ of product i to machine Y_k).

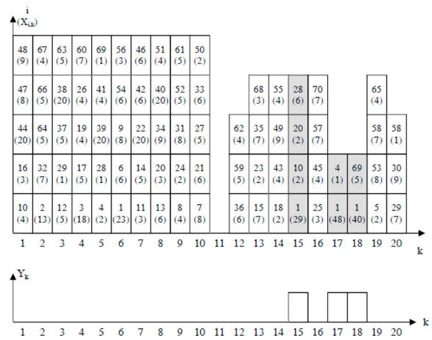

Fig. 5. Results for N3(machines changeovers and change allocation of batch $X_{i,k}$ of product i to machine Y_k in gray).

Computational experiments were based on the past experience of the authors (Wikarek 2014, Sitek and Wikarek 2015) and carried out using three MP solvers: LINGO, SCIP and Gurobi. Analysis of the results confirms the suitability of the proposed model both in the scope of supported decisions as well as calculation efficiency. For this problem structure, Gurobi solver proved to be the best.

6. CONCLUSIONS

Given the results presented, the following conclusions are offered:

- The proposed model for architecture and parameterization is characterized by great versatility.
- The proposed question set supports a wide range of decisions related to the configuration of the manufacturing system.

The most important are the decisions regarding the setup/changeover and optimum setup/changeover of the system in the context of the production of a given set of products, determination of the allocation of product batches to specific machines, optimization of the system configuration (minimizing the number of machine changeovers), etc. Another type of decisions are influenced the process control –sequencing, routing and intralogistics. These decisions concern the selection of a system configuration that guarantees the execution of a set of orders at the resources held and at the reduction of their number and/or production capacity.

Further work will focus on applying the model to dedicated manufacturing systems (Nielsen et al. 2014), supply chains (Sitek et al. 2017) and introducing fuzzy logic (Kłosowski et al 2016).

REFERENCES

Abazari A.M, Solimanpur M., Sattari H. (2012). Optimum loading of machines in a flexible manufacturing system using a mixed-integer linear mathematical programming model and genetic algorithm. In *Computers & Industrial Engineering*, 62(2), 2012, 469-478.

Ammons, J. C., Lofgren, C. B., McGinnis, L. F. (1985). A large scale machine loading problem in flexible assembly. In *Annals of Operations Research*, 3, 319–322.

Biswas, S., Mahapatra, S.S. (2008). Modified particle swarm optimization for solving machine loading problems in flexible manufacturing systems. In *International Journal of Advanced Manufacturing Technology*, 39, 931–942.

Bocewicz, G., Banaszak, Z., Nielsen, I. (2015) Multimodal processes prototyping subject to fuzzy operation time constraints. In *INCOM 2015,* 48(3), 2103-2108.

Chan, F.T.S., Chan, H. K. (2004). Analysis of dynamic control strategies of an FMS under different scenarios. In *Robotics and Computer Integrated Manufacturing*, 20(5), 423–437.

Chan, F.T.S, Swarnkar, R. (2006) Ant colony optimization approach to a fuzzy goal programming model for a machine tool selection and operation allocation problem in an FMS. In *Robot Comput Integr Manuf*, 22(4):353-362.

Gola, A. (2019) Reliability analysis of reconfigurable manufacturing system structures using computer simulation methods. In: Eksploatacja i Niezawodnosc – Maintenance and Reliability 2019; 21 (1): 90–102.

Kazerooni A., Chan F.T.S. Abhary K. (1997). A fuzzy integrated decision-making support system for scheduling of FMS using simulation. In *Computer Integrated Manufacturing Systems*, 10(1) 27-34.

Kłosowski, G., Gola A., Świć A. (2016) Application of Fuzzy Logic in Assigning Workers to Production Tasks. In *Distributed Computing and Artificial Intelligence, 13th International Conference*, Springer Series: Advances in Intelligent Systems and Computing, Vol. 474, 505-513.

Nielsen, I., Dang, Q., Nielsen, P., Pawlewski, P. (2014) Scheduling of mobile robots with preemptive tasks. In *Advances in Intelligent Systems and Comp*uting, 290, 19-27. doi:https://doi.org/10.1007/978-3-319-07593-8_3

Sarin, S. C., Chen, C. S. (1987). The machine loading and tool allocation problem in flexible manufacturing system. In *International Journal of Production Research*, 25, 1081–1094.

Schrijver, A. (1998) Theory of Linear and Integer Programming, ISBN 0-471-98232-6, John Wiley & sons.

Sitek, P., Wikarek, J. (2015) A novel approach to decision support and optimization of group job handling for multimodal processes in manufacturing and services. In *15th IFAC INCOM 2015,* 48(3), 2115-2120 doi; https://doi.org/10.1016/j.ifacol.2015.06.401

Sitek, P., Wikarek, J., Nielsen, P. (2017) A constraint-driven approach to food supply chain management. In: *Industrial Management & Data Systems*, 117(9) 9, 2115-2138, https://doi.org/10.1108/IMDS-10-2016-0465

Stecke, K. E. (1983). Formulation and solution of non-linear integer production planning problem for flexible manufacturing system. In *Management Science*, 29, 273–288.

Yogeswaran, M., Ponnambalam, S.G., Tiwari, M. K. (2007). A hybrid heuristic using genetic algorithm and simulated annealing algorithm to solve machine loading problem in FMS. *In IEEE conference on automation science and engineering*, Scottsdale, AZ, USA, September 22–25.

Wikarek, J., (2014) Implementation Aspects of Hybrid Solution Framework, AICS vol 267, 2014, pp. 317-328. doi: https://doi.org/10.1007/978-3-319-05353-0_31