MODELLING AND SIMULATION OF RECONFIGURABLE MANUFACTURING SYSTEM FOR MACHINING OF CASING-CLASS PARTS

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Abstract. As the sale of agricultural machinery and spare parts is a highly seasonal business, manufacturing companies need to respond to the changing market demand by adjusting their production level in a cost-effective and flexible manner (to reduce storage costs). In view of this, designers of manufacturing systems must embrace the challenge of designing modular systems, which structure can be quickly adapted to the changing product range and production volume. One approach that addresses this challenge is the concept of reconfigurable manufacturing systems (RMS), which was developed at the end of the 20th century. The key characteristics of RMS are modularity, integrability, customized flexibility, convertibility, scalability and diagnosability, all of which are consistent with the assumptions of the philosophy of Industry 4.0. These features – alongside the adjusted system's capacity and flexibility to current manufacturing needs – allow to extend the life cycle of a designed system. The aim of this paper was to enable (using computer simulation method) the selection of an RMS structure what will correspond to the expected characteristics determining the throughput of the system under design and to select the most appropriate cycle time that allows to reduce the necessary capacity of buffers between the next stages of the designed system. In particular, eight RMS structures using Tecnomatix Plant Simulation software were modelled and the system's throughput for each of those structures was analysed. As a part of presented conclusions, general guidelines how to choose the best structure during the process of reconfigurable manufacturing system's design have been pointed out.

Keywords: reconfigurable manufacturing system, RMS, design, simulation, throughput, productivity.

Introduction

At the end of the 20th century, manufacturing companies entered a new era, which, on the one hand, offered tremendous technical and IT solutions, but, on the other brought them into competition with other firms not only on a local and national, but also a global level [1; 2]. To remain competitive, companies had to design manufacturing systems that not only produced high-quality products at low costs, but also allowed to produce a wide range of different products (often characterized by the high level of seasonality) using the same system [3; 4]. Although the idea of flexible manufacturing systems (FMSs) allowed to produce a variety of goods belonging to a defined family of a specific class of products, those systems turned out to be costly, most particularly because the equipment that possessed features enabling general flexibility that was expensive to build and maintain [5; 6].

Both, to eliminate the negative characteristics of FMSs and to catch the light of the prospects for the development of industry in line within 4.0 paradigms, at the turn of the 21st century a new concept of reconfigurable manufacturing systems (RMSs) has been developed [7]. By definition, these systems are designed for rapid change in structure that allows to adjust the system's functionality and production capacity to the current production requirements what allows to limit the investment costs [8]. Among other conceptions of modern manufacturing system design and operations, the idea of RMSs is the fastest developing one and many of researches are conducted in this field [9].

In overall, designing of reconfigurable manufacturing systems is a complex multi-level procedure influenced by a large number of factors. Designing requires an in-depth analysis of market targets and possible ways of preparing and implementing usually automated and robotized manufacturing systems, assessing the impact of crucial factors, as well as integrating the knowledge of many branches of science and individual decisions [10]. In designing RMS, designers usually focus on optimal selection of the system's physical components, such as machine tools and means of in-plant transport, and their optimal arrangement in order to meet pre-defined production requirements [11]. A key issue in designing RMS is the selection of an appropriate production structure that enables the manufacture of products with an assumed efficiency, while allowing to maintain the principles of the reconfigurable manufacturing system [12; 13]. Unfortunately, although this problem has been the subject of numerous studies for over a dozen years now, only general assumptions regarding the optimal selection of and RMS configuration have been defined and there is no complex methodology concerning the problem of proper selection of RMS structures [14].

This paper focuses on how the production structure (including the transport subsystem) of an RMS system being designed affects the level of its throughput when compared different possible system's structures. The essence of the proposed approach is to enable the selection of an RMS structure what will correspond to the expected characteristics determining the throughput of the system under design and to select the most appropriate cycle time that allows to reduce the necessary capacity of buffers between the next stages of the designed system. For provided research methods computer simulation was used.

Idea and principles of reconfigurable manufacturing systems design

The concept of reconfigurable manufacturing systems was created in the Engineering Research Centre at the University of Michigan College of Engineering (USA) and was implemented in 1999 as a response to new market challenges [15]. The basic features of RMS include [16]:

- Modularity – all the main components of a system (both hardware and software) have a modular structure. Modularity makes it possible to easily change the structure of a system or device in order to adjust it in the best possible way to the current production requirements.
- Integrability – the ability to quickly and precisely integrate modules by a set of mechanical, informational and control interfaces that enable their integration and communication.
- Customization – system flexibility is designed around the current production needs.
- Convertibility – the ability to quickly change the functionality of the existing system, machines and controls to suit new production tasks.
- Scalabiltiy – the ability to easily change the production capacity of an RMS by changing its structure or the production capacity of its specific components.
- Diagnosability – the ability to automatically read the current state of the system and to detect and diagnose the causes of output products and take corrective action immediately.

An RMS is composed of workstations which are reconfigurable machine tools, a control system consisting of reconfigurable machine tools, a control system consisting of reconfigurable controllers for the control of the reconfigurable machine tools, and a reconfigurable material transport and handling subsystem, controlled by the control system, for automated transport of materials and workpieces within the RMS. A typical RMS consists of up to 20 stages with the machine tools of each stage having identical functional features (Fig. 1). In the machining process parts are moved from one stage to the next using conveyors or overhead cranes.

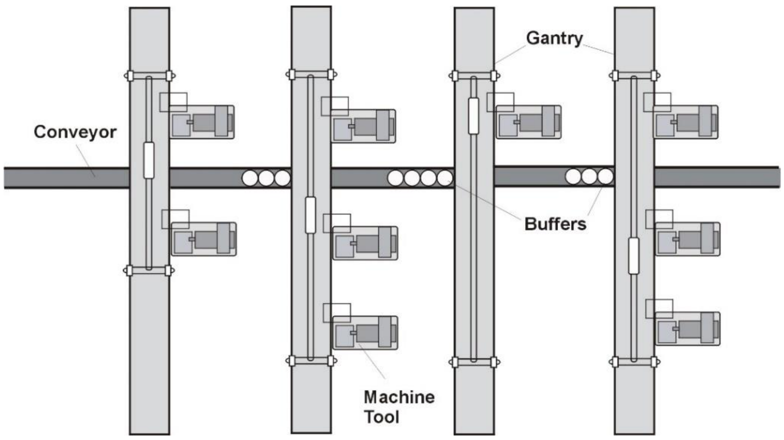

Fig. 1. **Schematic of arrangement of structural components of RMS [14]**

Thanks to customization, the functionality and production capacity of RMS are strictly adjusted to current production tasks. As a consequence, these systems have a minimum required level of flexibility, which limits the investment costs. Owing to their modularity, integrity, scalability and convertibility, however, they can be quickly redesigned to achieve a new, desirable level of functionality and production capacity suited to new market requirements.

Research problem

Reconfigurable manufacturing systems can be designed in many configurations: serial, parallel or hybrid. The different configurations have a considerable impact not only on the possibility of adapting production to market needs, but also on the reliability, productivity, product quality and cost of production [17].

In this study we analyzed the problem of selecting structures for the reconfigurable manufacturing system defined in article [8]. The analyzed RMS is dedicated for casing-class machining with dimensions 700 mm x 500 mm x 400 mm (Fig. 2 a). The technological process encompassed five technological operations performed on two faces of a part. Each face requires separate fixturing (Fig. 2 b). The design assumed that the system should be capable of producing 500 parts a day. The working time per day for the manufacturing system (Fj) was 16 hours 40 minutes. The maximum allowable cycle time for producing 500 parts in that time was $\tau_{max} = 2$ min./part.

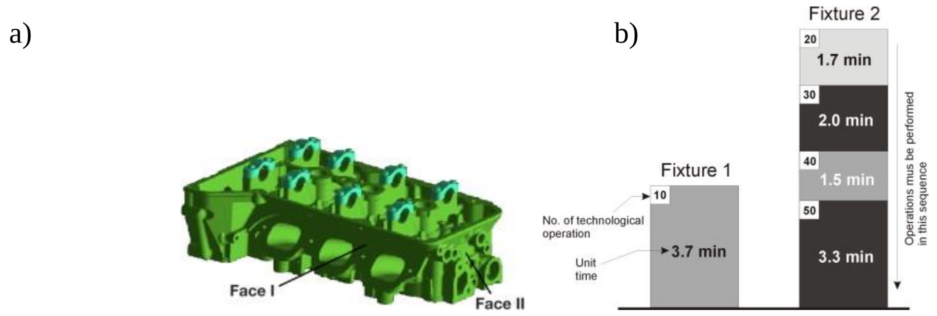

Fig. 2. **Casing-class part to be manufactured in RMS: a) general schematic view of the product, b) structure of the product's technological process [16]**

As previous analyses and research findings for the analysed RMS (see: [8,13]) show, the required throughput level of 500 parts a day can be achieved using one of the eight structures shown in Fig. 3. However, this must be emphasized that provided results do not consider the transport and handling subsystems. As the consequence they cannot be treated as a final one and it is necessary to make deeper analysis to define the throughput of the whole system (including machine tools, transport and handling subsystems).

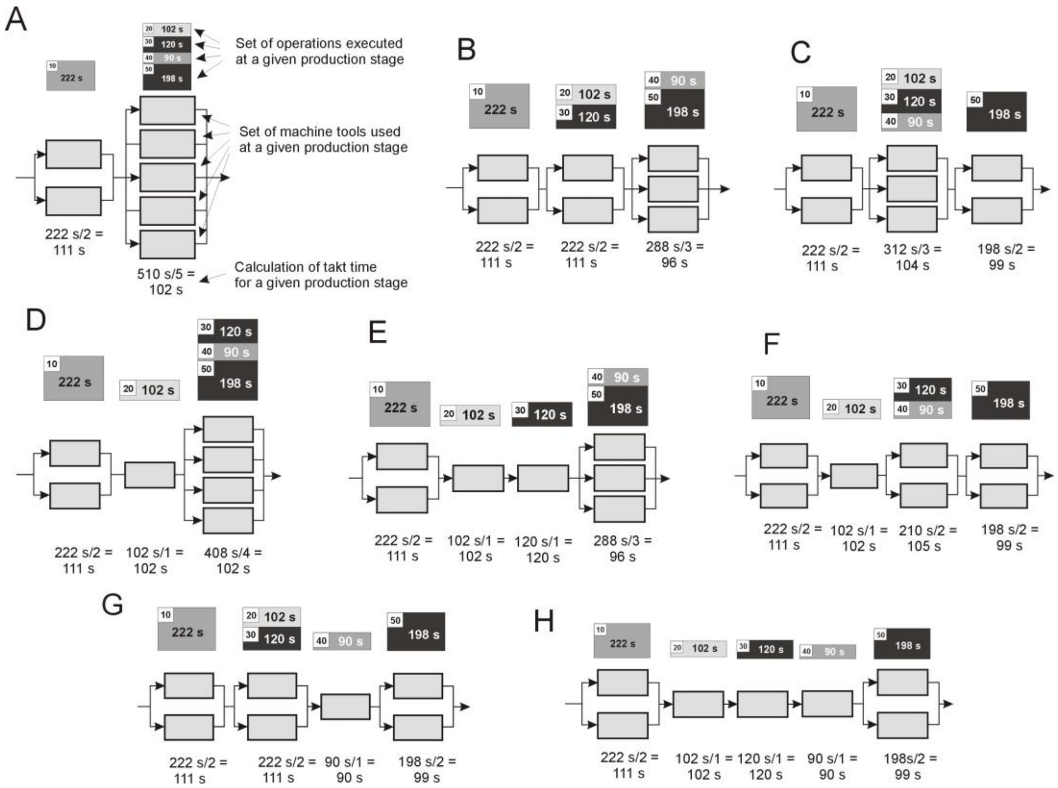

Fig. 3. **RMS structures analysed in this study [16]**

Analysis of throughput of RMS system structures – results of simulation experiments

To assess the level of throughput of the designed system the method of computer simulation was used. For each of analyzed structure the simulation model that comprises the machine tools, transport and handling subsystems was developed (Fig. 4). When designing the system, it was assumed that the transport of the parts between following stages of the system is realized using the conveyors of 5 meters length, while loading and unloading of parts in each of the stage is realized using gantries of module structure (such a structure allows an easy reconfiguration when the number of machine tools must be changed).

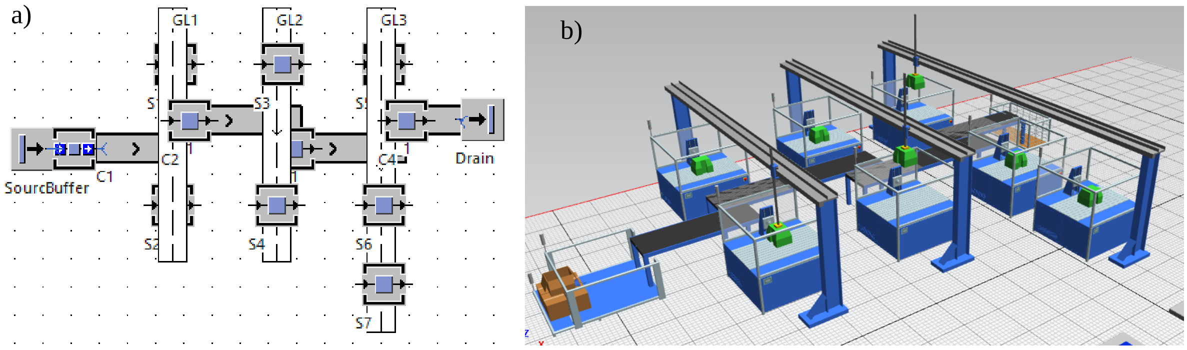

Fig. 4. **Example of simulation model for configuration B developed using Tecnomatix Plant Simulation software:** a – 2D model; b – 3D model

The analysis was provided to check both the throughput of the system and the occupancy rates of conveyors in bottlenecks of the system. The experiments have been done for each of configuration for the cycle times from 100 to 140 seconds. The summary of example results of provided simulation experiments is presented in Table 1.

Table 1

Results of simulation experiments

	Configuration																	
	A		**B**		**C**			**D**		**E**		**F**		**G**		**H**		
Cycle time	**Throughput**	**Buffer (bottle neck 1)**	**Throughput**	**Buffer (bottle neck 1)**	**Throughput**	**Buffer (bottle neck 1)**	**Throughput**	**Buffer (bottle neck 1)**	**Throughput**	**buffer (bottle neck 1)**	**Bufffer2 (bottle neck 1)**	**Throughput**	**buffer (bottle neck 1)**	**Throughput**	**buffer (bottle neck 1)**	**Throughput**	**buffer (bottle neck 1)**	**buffer (bottle neck 1)**
100	493	85	492	84	492	85	492	85	443	85	50	492	85	492	85	443	85	50
102	493	76	492	76	492	76	492	76	443	76	50	492	76	492	76	443	76	50
104	493	68	492	68	492	68	492	68	443	68	50	492	68	492	68	443	68	50
106	493	60	492	60	492	60	492	60	443	60	50	492	60	492	60	443	60	50
108	493	52	492	52	492	52	492	52	443	52	50	492	52	492	52	443	52	50
110	493	43	492	43	492	43	492	43	443	43	50	492	43	492	43	443	43	50
112	493	35	492	35	492	35	492	35	443	35	50	492	35	492	35	443	35	50
114	493	27	492	27	492	27	492	27	443	27	50	492	27	492	27	443	27	50
116	493	18	492	19	492	18	492	18	443	18	50	492	18	492	18	443	18	50
118	493	11	492	11	492	11	492	11	443	11	50	492	11	492	11	443	11	50
120	493	1	492	1	492	1	492	1	443	1	50	492	1	492	1	443	1	50
122	486	1	486	1	486	1	486	1	443	1	43	486	1	486	1	443	1	43
124	478	1	478	1	478	1	478	1	443	1	35	478	1	478	1	443	1	35
126	470	1	470	1	470	1	470	1	443	1	28	470	1	470	1	443	1	28
128	463	1	463	1	463	1	463	1	443	1	20	463	1	463	1	443	1	20
130	456	1	456	1	456	1	456	1	443	1	13	456	1	456	1	443	1	13
132	449	1	449	1	449	1	449	1	443	1	6	449	1	449	1	443	1	6
134	442	1	442	1	442	1	442	1	442	1	1	442	1	442	1	442	1	1
136	436	1	436	1	436	1	436	1	436	1	1	436	1	436	1	436	1	1
138	430	1	429	1	429	1	429	1	429	1	1	429	1	429	1	429	1	1
140	424	1	423	1	423	1	423	1	423	1	1	423	1	423	1	423	1	1

The obtained results of the simulation experiments show that none of the analyzed configurations of the system gives the possibility of gaining the necessary throughput of the system. The highest throughput was noticed, or the two-stage configuration, and it equals 493 pieces/day, while the lowest one was noticed for structures E and H (the maximum throughput for these configurations equals 443 pieces/day) – see. Fig. 5.

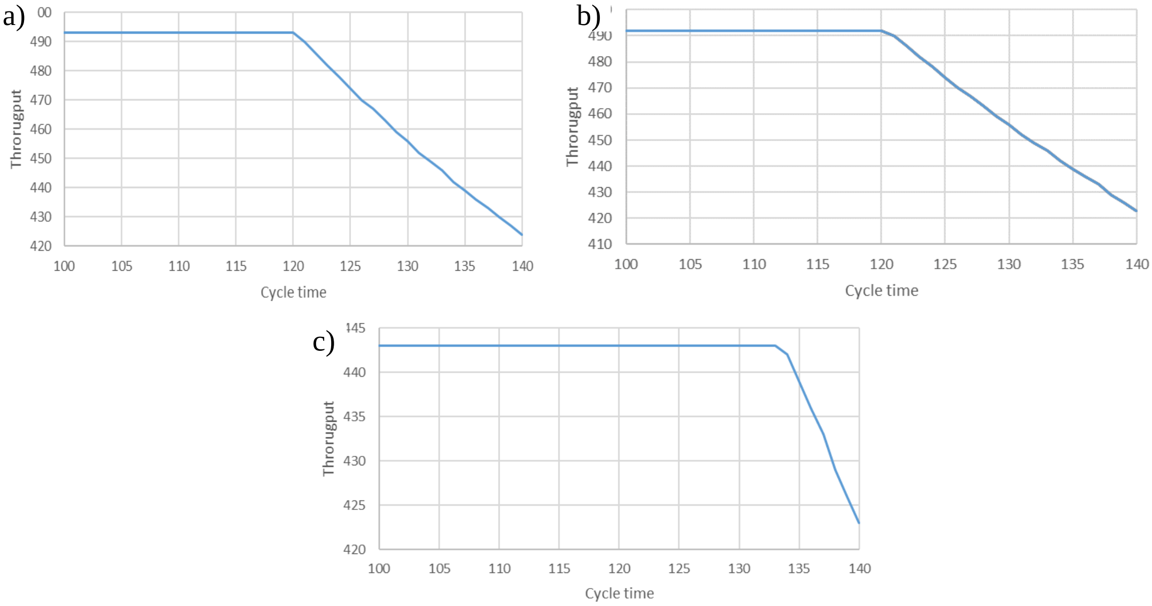

Fig. 5. **Relationship between cycle time and throughput of RMS:** a – for configuration A; b – for configurations B,C,D,F,G; c – for configurations E and H

In case of configurations A,B,C,D,F and G defining the interval of introducing the semi-finished products into the system below 120 second causes gathering the parts on the conveyor 1 without increasing the throughput of the system (Fig. 6a). It indicates that is not recommended to reduce the interval of introducing the semi-final products into the system to the theoretically best value of 111 seconds (at this value of interval the necessary capacity of the conveyor is 39 pieces). The production process realized into the RMS built using the structure A with the defined cycle times of 120 seconds allows to provide fluent production process with the usability of machine tools at the level of over 90% in stage I and over 80% of usability in stage II (Fig. 6b). In case of gantries their actual usability is below 10% that gives the possibility of further expansion of the system without necessity of using additional transport equipment (Fig. 6c).

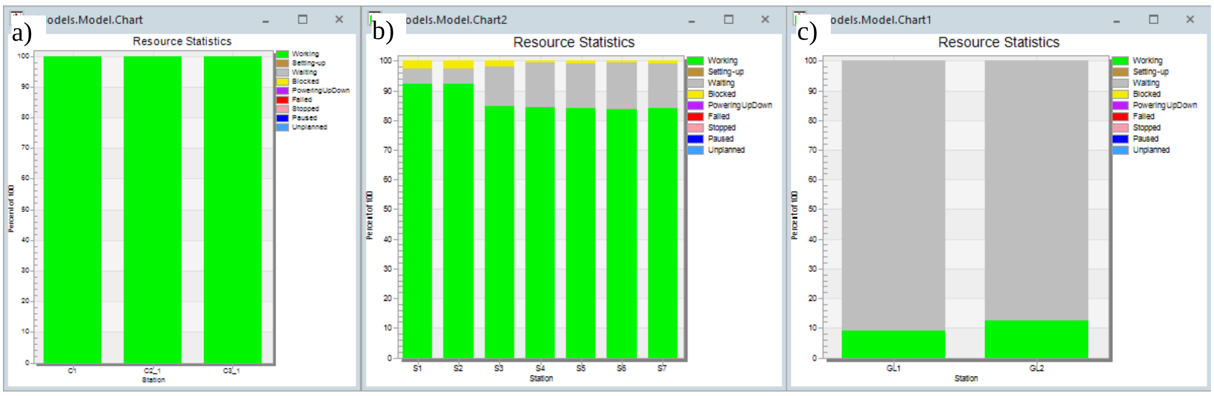

Fig. 6. **Level of usability of particular elements of designed RMS for configuration A with defined cycle time of 120 s: a) conveyors, b) machine tools, c) gantries**

Conclusions

The provided research allows to draw the following conclusions:

1. Methods of computer simulation give the possibility of estimation the expected throughput and usability of the system and all elements that are included into the system.
2. The analyzed case shows that the systems of fewer number of stages are more productive. While the two-stages structure gives maximum throughput of 493 parts per 1000 min., the five-stages structure gives the expected throughput of only 443 parts per 1000 min.
3. The simulation experiments give a possibility to define the proper level of interval of introducing semi-final products to reduce the necessary capacity of conveyors of buffers between stages of the system. In the analyzed RMS the most suitable interval for structures A,B,C,D,F,G is 120 seconds, while 133 seconds for structures E and H.

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