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A SIMULATION STUDY OF INDUSTRY 4.0 FACTORIES BASED ON THE ONTOLOGY ON FLEXIBILITY WITH USING FLEXSIM® SOFTWARE

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Abstract
The main aim of the article is to develop a simulation model of flexible manufacturing system with applying the ontology on flexibility. Designing manufacturing systems matching both production and market requirements becomes more and more challenging due to the variability of demand for a large number of products made in many variants and short lead times. Manufacturing flexibility is widely recognised as a proven solution to achieve and maintain both the strategical and operational goals of the companies exposed to global competition. Generic simulation model of flexible manufacturing system was developed using FlexSim® 3D software, then the example data were used to demonstrate the developed model applicability. "The Ontology on Flexibility" was applied for evaluation of achieved flexibility of manufacturing system.

Keywords
Industry 4.0, Simulation Modelling, Flexible Manufacturing System, FlexSim®.

Introduction

Digital transformation of the production company under the influence of the development of flexible manufacturing systems with applying advanced information and communication technologies (ICT) in production automation creates a new paradigm of production systems, which is defined through an umbrella framework heading as the Industry 4.0 (ger, *Industrie 4.0*). The term was coined in the *German High-Tech-Strategy 2020* presented during Hannover-Messe Fairs 2011 [1]. Accordingly, to the original definition [2], *Industrie 4.0* refers to the intelligent networking of machines and processes for the industry with the help of information and communication technologies. German Federal Ministry for Economic Affairs and Energy (BMWi) published new agenda for economy digitisation in which expands Industry 4.0 definition to express that it "describes a fundamental process of innovation and transformation in industrial production (...) driven by new forms of economic activity and work in global, digital ecosystems" [3].

Industry 4.0 (I4.0) is a collective term for the technology and concept of value chain organisation, which includes four key elements [4]: Smart Factories, Cyber-Physical Systems (CPS), Internet of Things (IoT), and Internet of Services (IoS). Production in I4.0 can be considered as the intelligent flow of the workpieces machine-by-machine in a factory, supported by real-time communication between machines [5]. Collaborative manufacturing, along with computer-based distributed management, operationalizes Industry 4.0 concept [6]. Cyber-Physical System is a mechanism controlled or monitored by computer algorithms; CPS integrates computational (cyber) world and physical world. Physical processes are a source of data for computational processes that generate control signals appropriate to the results of calculations [7]. Cyber-physical system-based automation means the integration of homogeneous sources of information from PLC controllers, supervisory control and data acquisition (SCADA), manufacturing execution system (MES), enterprise resource planning (ERP) systems, and streaming data from networked sensors placed among and in manufacturing resources. Integrated through time-stamping, cleaned, and structured data are supplied to the enterprise data repository (Data Lake) for Business Intelligence, Big Data, cognitive processing with using artificial intelligence (AI) technologies, or traditional data processing purposes. Mass product personalisation, flexibility in adapting production capacity to demand volume, ability to cost-effective unit production on an industrial scale. "Batch size 1" production require continuous monitoring and planning to improve production efficiency from an operational management perspective. Real-time data from CPS production systems can be used to drive mirrored-in-software physical objects called digital twins to analyse and simulate real-world environment and events [8, 9]. A holistic theory of production combines deterministic and cybernetic models to enable an integrative comprehension and learning process in order to predict and control the behaviour of complex production systems [10]. Industrial plants (assets, inventories, production and assembly lines) need to be designed, monitored and maintained with applying integrated and scalable digital factory models with multi-level semantic access to all the factory resources (i.e. assets, machines, workers and objects) [11, 12].

The main aim of the article is to develop a simulation model of flexible manufacturing system using FlexSim® 3D software. The flexibility of manufacturing system was evaluated with applying the ontology on flexibility.

The ontology on flexibility for manufacturing systems

Variety oriented manufacturing driven by mass customisation manufacturing paradigm in the 90' of the XX century and the extreme variety of personalised production in XXI century results with the co-evolution of products and manufacturing systems [13]. Designing manufacturing systems matching both production and market requirements becomes more and more challenging due to the variability of demand for a large number of products made in many variants and short lead times. Manufacturing flexibility is widely recognised as a proven solution to achieve and maintain both the strategical and operational goals of the companies exposed to global competition. Modern manufacturing systems achieve adaptation to volume and product variety in three ways [13]: (1) pre-planned generalised flexibility of flexible manufacturing systems (FMS), (2) limited/focused flexibility to suit a narrower scope of products variants, or (3) customised flexibility on-demand by physically reconfiguring a manufacturing system. In general, the above concepts are covered by an umbrella framework named Changeable manufacturing systems (CMS). FMS is a highly automated manufacturing system designed and built-in a priory for pre-defined anticipated product variants over a certain period without physically changing the manufacturing system itself [1, 14]. FMSs *consist of a set of flexible machines (robot, multi-purpose machines or workstations), an automatic transport system and a decision-making system (scheduler) to decide at each instant (When) what has to be done (What) and on which machine (Where)* [15]. FMS implementation in the industry is based on the use of a fully computer integrated manufacturing system consists of a set of computer numerically controlled (CNC) machines, interconnected by an automated material handling system. The manufacturing *flexibility forms* presented in the industry are as follows [16, 17]: Routing flexibility; Mix flexibility; Product flexibility; Volume flexibility; Focused flexibility; Assembly flexibility etc. Terkay et al. [16] introduced *The Ontology on Flexibility* to analyse real production systems. According to this approach, we can consider each form of flexibility observed in the real-world as a *Compound Flexibility Form* obtained by combining some *Basic Flexibility Forms* defined as the aggregation of two key concepts: *Dimensions* and *Levels*. There are four basic flexibility dimensions defined as [16]:

- Capacity – The system can do the same products at a different scale;
- Functionality – The system can do different things due to different features;
- Process – The system can obtain the same thing in different ways;
- Production planning – The system can change the order of execution or the resource assignment to do a given set of things.

Each basic flexibility dimension is specified by four attributes: Range, Uniformity, Mobility, and Resolution, which are defined as follows:

- Range represents an extension of differences among the various ways of behaving under a given dimension;

- Mobility expresses the ease with which it is possible to modify the behaviour under a given dimension;
- Uniformity expresses the variability of performance of the system due to mobility;
- Resolution expresses how close the alternatives are within the range of given dimensions.

Concept of flexibility levels is related to the real implementation of various form of FMSs [16]:

- Level 1: Flexibility;
- Level 2: Reconfigurability;
- Level 3: Changeability.

Due to this model, we can proceed with flexibility analysis for each basic dimension separately and establish a level of flexibility for each of them. As a result, we can obtain a detailed characterisation of the flexibility of the manufacturing system.

Research methodology

Computer simulation is intermediate between theory supplied by analytical means and observations; gives the alternative way for finding problem solution through experiments with a model. A simulation is *the imitation of the operation of a real-world process or system over time* [18]. Extended definition of computer simulation including four aspects of simulation (operations systems, purpose, simplification, and experimentation) is as follows: *experimentation with a simplified imitation (on a computer) of an operations system as it progresses through time, for (…) better understanding and (or) improving that system* [19]. Figure 1 introduces a process diagram of a simulation study presented with Business Process Model Notation (BPMN).

FlexSim® 3D Simulation software package was used for computer modelling and discrete simulation purposes. FlexSim enables modelling and discrete-time simulation with visualisation in 3D technology, including virtual reality experience. Realistic graphical 3D animation and extensive performance reports (customised dashboards) allow through a series of simulations to track problems and find alternative solutions in a relatively short amount of time. There

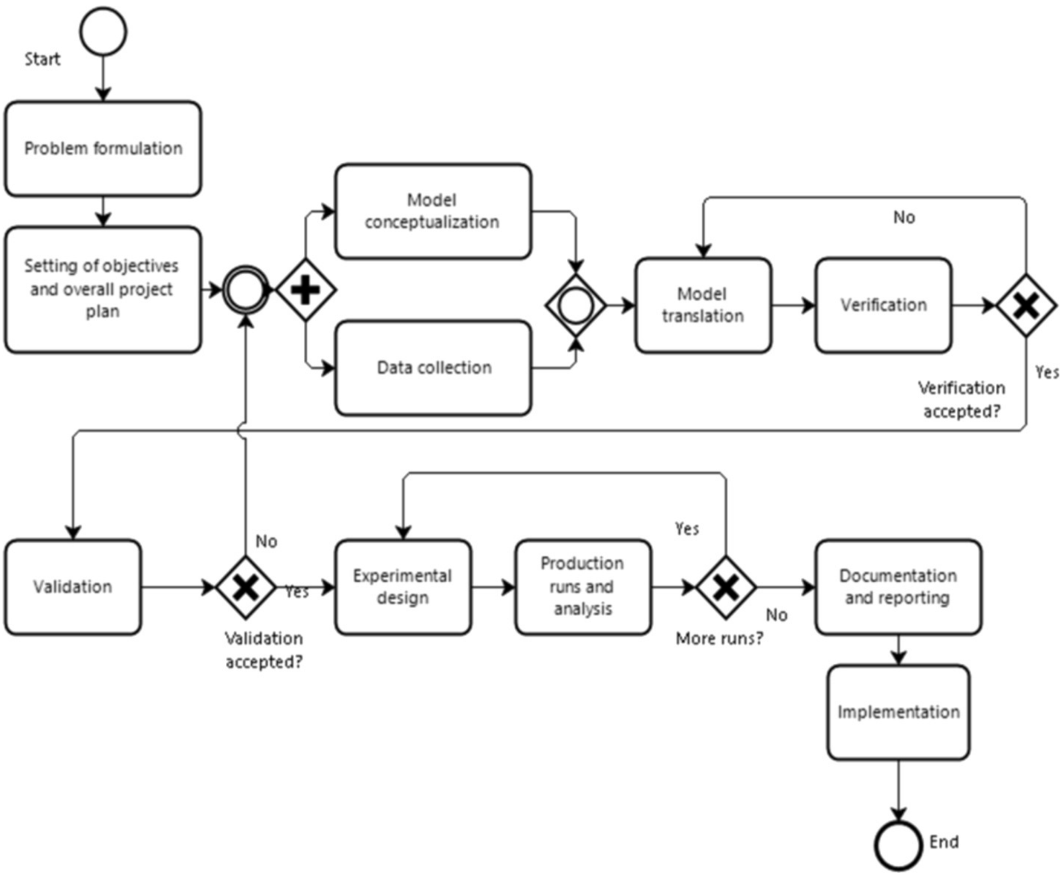


Fig. 1. The process of a simulation study.

are three tools available to employ optimisation methods for simulation modelling with FlexSim [20]: 1) Simulation Experimenter Control tool with build-in OptQuest (requires an additional license) that solves problems with evolutionary algorithms, 2) Flexiscript (internal script language) to batch processing, exchange of data with third-party software and advanced customisation; 3) external DLLs (dynamic-link libraries) to combine FlexSim and Matlab (or Scilab) to handle linear programming optimisation or simulation analysis. Since the year 2017, the emulation tool to control 3D models with simulated programmable logic controllers (PLC) was introduced to FlexSim as well as the interface for exchange of all sensors and controls PLC data directly (through serial communication protocol Modbus) or with OPC communication server. It makes FlexSim digital-twin ready software [21].

Problem statement

The reference manufacturing system consists of production resources, storage spaces including buffer slots, transport systems to support raw material supply, and circulation of work-in-progress parts. Two problems are investigated during the modelling process with FlexSim: implementation of flexible routing, transport system topology and control strategy. There are three cells M1, M2, M3 – each equipped with computer numerical control (CNC) machining center that combining drilling, milling, and boring operations. Each cell is provisioned with a unique set of tools to perform several operations. Automated guided vehicles (AGVs) are used for internal transportation and logistics purposes. AGVs use fixed routes.

Let consider an example of a production cycle of 120 products as a mix of three types. The specification of product routing due to the type of product is given in Table 1.

Machining unit times for each technological operation performed in a particular cell on a specific type of product are given in Table 2.

Table 1
Product routing.

Product type	Machine used
Type 1	M1, M2, M3
Type 2	M2, M1, M3
Type 3	M3, M2, M1

Table 2
Machining unit times [s].

Product type	Machine		
	M1	M2	M3
Type 1	15	10	11
Type 2	8	13	5
Type 3	12	13	11

Computer model

The screenshot of the simulation surface captured during simulation with a developed model of the reference production system is shown in Fig. 2.

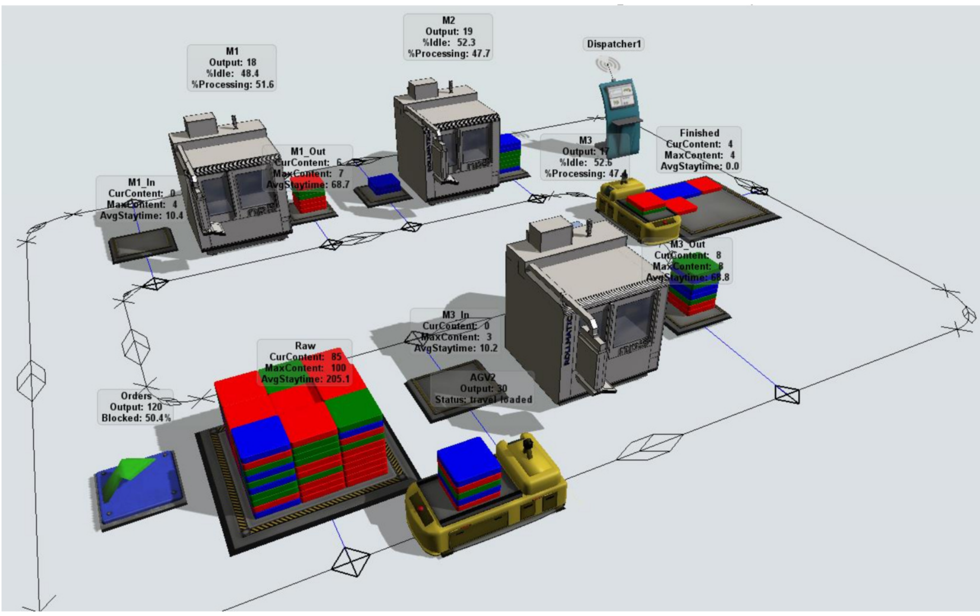


Fig. 2. A view of the model during simulation.

The Cellular manufacturing approach was used for the layout of the reference production system. Ushape topology was applied with combining CNC machining centers and storage fields for achieving proximity to reduce wasted motion. It is a suitable solution for low volume and high mix job shops. Models developed in graphically oriented simulation environment of FlexSim consist of basic elements, called objects, that represent equipment, or performs a specific function on the simulation surface. There are also flow elements, called *flowitems* [20], that interact with objects in a simulation. Flowitems may have user-defined data on them called labels. Fixed resources are the objects that send, receive, and perform activities/operations on flowitems. A list of fixed resources employed in the model is given in Table 3.

Table 3
Fixed resources.

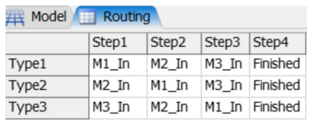
Objects names	Type	Description
Orders	Source	Represents production orders release
Raw	Queue	Represents storage field for raw materials due to released orders
M1, M2, M3	Processor	Represent CNC machining centers
M1_In, M1_Out, M2_In, M2_Out, *M3_In, M3_Out*	Queue	Represent input and output buffer-slots for each CNC machining centers
Finished	Queue	Represents storage field for finished products

The variability of the product was introduced to the model through the appropriate definition of flow elements. Object *Orders* creates and releases 120 flowitems of three types vivid as cuboids with three different colours. Flowitems represent a mix of production orders for three types of products. Each flowitem has two user-defined labels: label "Type" with a value assigned with the *duniform* distribution strategy from the set $\{1, 2, 3\}$; label "StepNr" with initiation value equals 1. Label "Type" stores a numerical code of product type. Label "StepNr" stores the current step of the manufacturing process for each flowitem.

User-defined information sticking to flowitem objects can be considered as a functional model of applying radio-frequency identification (RFID) technology in manufacturing systems. The primary function of the RFID is automated identification and data capture. According to the Industry 4.0 paradigm, the flow of the work-in-progress can be tracked and controlled using RFID tags and transponders. RFID tags extend physical objects with a digital component that is instantly available for computer control systems via networked transponders placed in a manufacturing system. By analogy, user-defined data assigned to flowitems or objects are global (like global variables or attributes in programming languages) for the control mechanism of simulation.

Modelling and simulation of the variability of the manufacturing process were achieved by applying customised control to pulling and pushing the logic of fixed resources, which represent storage fields, buffer-slots, and CNC machining centers. Fixed resources have a built-in mechanism for implement topology of connections to move flowitems within the model. There are input and output ports to connect objects. Storage field *Raw* is connected with buffer-slots *M1_In, M2_In, M3_In* to supply CNC cells with raw material. Buffer-slots *M1_Out, M2_Out, M3_Out* are connected with buffer-slots *M1_In, M2_In, M3_In* to move work-in-progress and finally with storage field *Finished*. It is assumed that flowitems coined to the model as production orders are instantly (in zero time) transferred to the object Raw to represent raw materials in the storage field for production orders.

Dynamic routing for the manufacturing process was implemented as data-driven control with using GlobalTable objects of FlexSim software. Object *Routing* was created to store product routing given in Table 1 (Fig. 3).



	Step1	Step2	Step3	Step4
Type1	M1_In	M2_In	M3_In	Finished
Type2	M2_In	M1_In	M3_In	Finished
Type3	M3_In	M2_In	M1_In	Finished

Fig. 3. A screenshot of object *Routing* content.

The current destination for flowitem during simulation is on the intersection of type of the product (row) and the current step in the manufacturing process (column). The current step is incremented by one after finishing operation in CNC machines (*M1, M2, M3*) thanks to Triggers mechanism available in properties of fixed resources in FlexSim (Fig. 4).

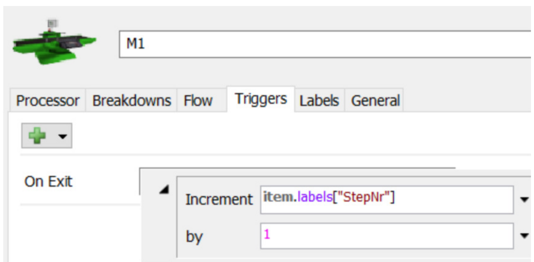


Fig. 4. A screenshot of object *M1* properties.

Properties of objects *Raw, M1_Out, M2_Out, M3_Out* were customised with code written in Flexiscript programming language. Developed code implements data-driven control for pushing flowitems due to identified topology of the current object's output ports (Fig. 5) and user-defined data of the current flowitem.

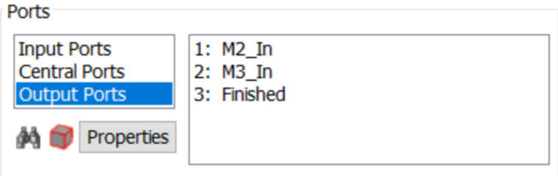


Fig. 5. A screenshot of object *M1_Out* properties.

Code snippet is as follows:

```
/**
Send to Port
Custom Code
*/
Object item = param(1);
Object current = ownerobject(c);
Variant tableID = "Routing";
Table table = Table(tableID.as(string));
Variant row = item.Type;
Variant col = item.StepNr;
string NextMachine = table[row][col];

for(int i=1; i <= current.outObjects.length; i++) {
   Object ConnectedPort = current.outObjects[i];
   if(NextMachine == getname(ConnectedPort)) {
     return i;
   }
}
```

Data-driven control with using GlobalTable object *UnitTime* was also used to customise the unit time of operations performed in CNC machining centers due to product type (Fig. 6).

Model | Routing | UnitTime

	M1	M2	M3
Type1	15	10	11
Type2	8	13	5
Type3	12	13	11

Fig. 6. A screenshot of object *UnitTime* content.

The transport subsystem of flexible manufacturing systems should support the movement of raw materials, semi-products, finished products, tools, post-production waste etc. Using two automated guide vehicles (AGV) in the developed model is proposed. AGVs are moving on two separate ellipsoids fixed routes: smaller, placed inside of U-shape cell and bigger, outside. The inner AGV is moving on minimal space and is dedicated to work-in-progress transportation. The outer AGV serves both for raw materials and semi-products motion. The proposed solution aims to increase flexibility and throughput of cellular manufacturing.

Configuration of the AGV transportation system is supported in FlexSim with a dedicated AGV module, including the possibility of implementing adaptative decision strategies for pick-up and drop-off operations. Thanks to that, in terms of flexibility, the transportation system can match manufacturing workstations. There are two Task Executors objects, named *AGV1* and *AGV2*, used in the developed model. Both were configured with the same parameters (Fig. 7).

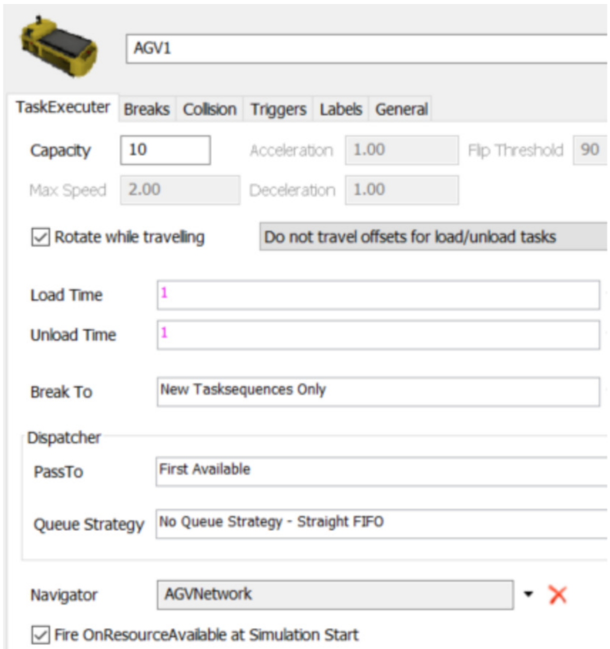


Fig. 7. A screenshot of object *AGV1* properties.

The Triggers mechanism available in properties of AGV was used to control unloading due to content in FlexSim (Fig. 8).

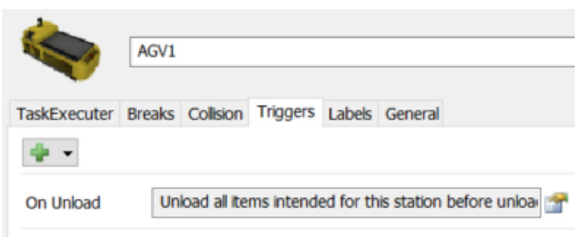


Fig. 8. A screenshot of object *M1* properties.

If AGV carries multiple flowitems, then a predefined trigger would cause to unload all flowitems intended for a current destination before moving on.

Model optimisation

The developed model of reference production systems was used in a series of simulation experiments. The basic run of simulation with initial data assumed during the model development produces relevant data collected and presented on the simulation dashboard shown in Fig. 9. It was assumed that maximum load (capacity) of AVGs is 120 pcs of flowitems. Overall cycle time for production 120 units of the mixed product takes 2203.31 [s].

FlexSim's Experimenter was employed to conduct optimisation of the maximum load of AVGs. The two independent variables were defined:

variable1 – MODEL:/AGV2>variables/maxcontent;

variable2 – MODEL:/AGV2>variables/maxcontent.

Respectively, *Finished products vs Time* was pointed out as Performance Measure. Then appropriate optimiser experiments were designed and run for 2203.31 [s] (Fig. 10).

The obtained results of optimisation are shown in Fig. 11.

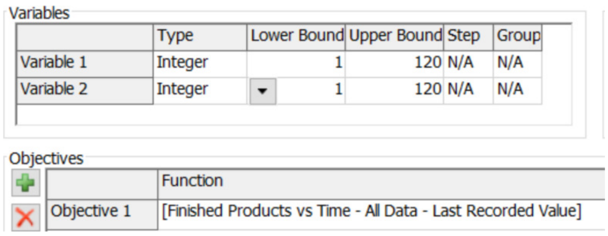


Fig. 10. A screenshot of the simulation experiment control.

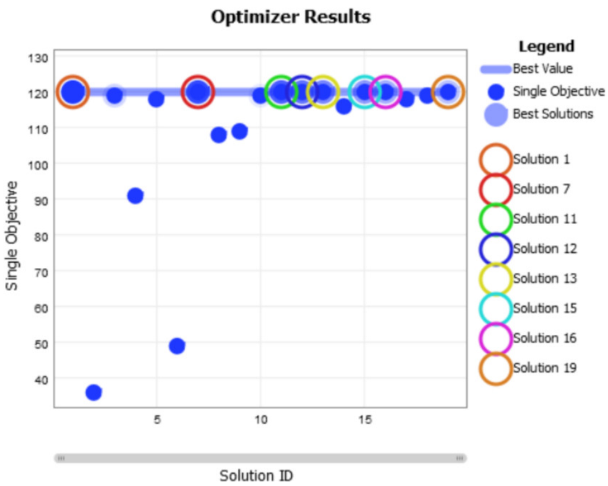


Fig. 11. A screenshot of FlexSim's optimiser results.

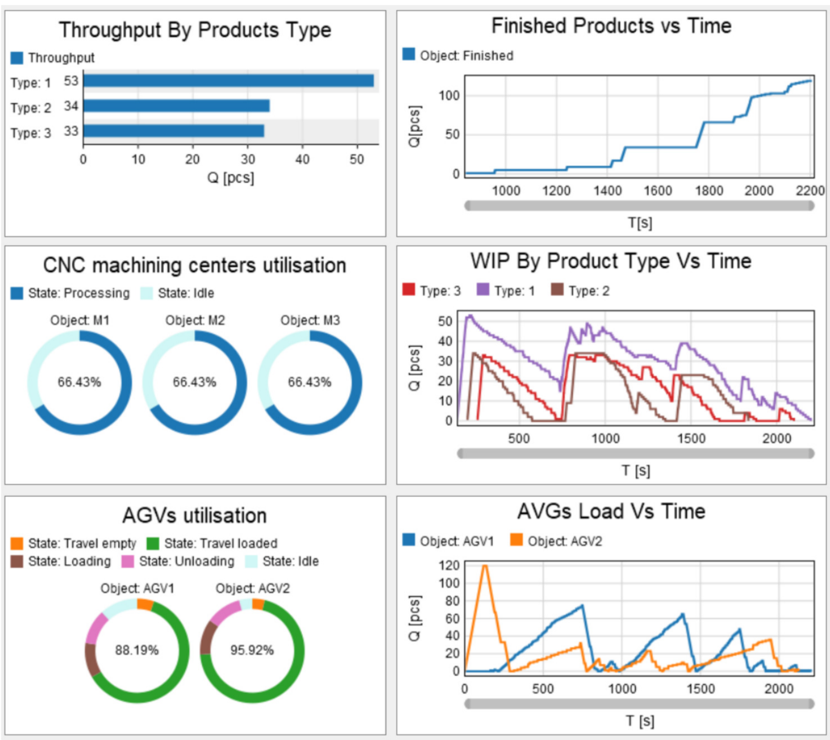


Fig. 9. A screenshot of the dashboard for a basic simulation run.

Fig. 12. A screenshot of the dashboard for simulation run after optimisation.

Among the best solutions, the *Solution 13* was the most appropriate, because of giving the lowest capacity for both of AVGs (Table 4).

Table 4
Optimisation's best solutions.

Solution ID	Variable 1	Variable 2
1	61	61
7	118	69
11	85	89
12	33	84
13	16	31
15	120	71
16	63	62
19	120	69

The final run dashboard for simulation with introducing optimised maximum capacity of AVGs is shown in Fig. 12.

Flexibility analysis of the model

The presented computer simulation model of FMS consists of CNC machining centres interconnected with AGV transportation system and with data-driven manufacturing execution mechanism implemented delivers Capacity, Functionality, Process and Production Planning flexibility. The model can simulate manufacturing of the same products at a different scale; it can adjust different production conditions, particularly batch size, level of productivity, etc. The functionality of CNC machining determines a wide spectrum of features and variety of products according to available tools set pre-defined for each CNC. The full flexibility in this dimension to extend the diversity of the products can be achieved through the implementation of tools supply due to service requests from particular CNC machine triggered by information carried by particular flow item in the FMS. The system can obtain the same thing differently due to functionality, but flexibility in this dimension is also limited: model dose does not implement adaptative routing strategy to accommodate to temporary machine out of service or balance utilisation of the CNC machining centres. It requires both extended Functionality flexibility and implementation of more appropriate algorithms for manufacturing execution control. Production planning flexibility is partially supported by default with FlexSim built-in simulation control mechanism. Advanced queuing strategies requires the implementation of customised algorithms.

The analysis of the flexibility of the reference production system model due to the flexibility levels is summarized in Table 5.

Table 5
Model flexibility analysis.

Dimension of flexibility	Evaluation
Capacity	Level 1 (Flexibility)
Functionality	Level 2 (Reconfigurability)
Process	Level 2 (Reconfigurability)
Production Planning	Level 2 (Reconfigurability)

According to results of an analysis of the basic flexibility dimensions embedded in the different compound flexibility forms [16]:

- 71.56% of the forms is characterised by Functionality flexibility;
- 23.85% of the forms is characterised by Capacity flexibility;
- 27.52% of the forms is characterised by Production Planning flexibility;
- 9.17% of the forms is characterised by Process flexibility.

Conclusions

The modelling of manufacturing systems is essential for introducing digital-twinning in digital transformation of the industry due to Industry 4.0 paradigm.

In the study carried out, it is demonstrated that it is possible to develop a computer simulation model of a flexible manufacturing system with FlexSim® software. Developed model flexibility was evaluated with using flexibility ontology approach. The highest level of flexibility was achieved in one of four dimensions. Identified gaps of flexibility require the implementation of appropriate representation, both physical and management solutions; the directions of future improvements were pointed out.

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