



## SEQUENCING AND PLANNING OF PACKAGING LINES WITH RELIABILITY AND DIGITAL TWIN CONCEPT CONSIDERATIONS – A CASE STUDY OF A SUGAR PRODUCTION PLANT

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**ABSTRACT. Background:** The study focuses on simplified make-and-pack production in the sugar industry as a case study. The analyzed system is characterized by parallel packing lines, which share one resource with a sequence-independent setup time. Additionally, the special characteristics that occur in many enterprises make scheduling difficult. The special characteristics of the system are the simultaneous occurrence of a variable input stream, scheduling of processes, and including the reliability of machines. Due to the variability of the input parameters, it is appropriate to consider the use of Digital Twin, which is a virtual representation of the real processes' performance. Therefore, this purpose of the paper is two-fold. First, an analysis of sequence determination of the stream-splitting machine was performed with taking into account the impact of logistics system reliability on system performance. Second, the concept of implementing Digital Twin in the analyzed production process is presented.

**Methods:** The mathematical model for line efficiency was developed on the presented make-and-pack production presented in the selected sugar industry. Different sequences of stream-splitting machines were studied to examine the system's efficiency, availability, and utilization of packaging lines. Two scenarios were investigated with the use of computer simulation.

**Results:** Computer simulation experiments were performed to investigate the sequencing and planning of packaging line problems. The results obtained for the case company indicated a significant dependence between the preferred packing sequence and the operational parameters.

**Conclusions:** The simulations confirm the influence of internal and external factors on sugar line packaging processes. The main advantage of the developed simulation model is identifying the relationship between the size of the input stream and the system's availability level, as well as identifying the main constraints on the possibility of implementing the DT concept in the analyzed company.

**Keywords:** production scheduling, sugar factory, make-and-pack production, food industry, Digital Twin, machine reliability

### INTRODUCTION

There is a growing need for manufacturing to become faster and more responsive to changes in the global market. These requirements are more and more often fulfilled by factory automation [Dotoli et al. 2019, Kopacek 2019], which is the basis of the Industry 4.0 concept. The future of enterprises is Smart Factory, which is full autonomy, starting with production planning and ending with its maintenance [VanDerHorn and Mahadevan 2021]. This automation is diverse in the food industry, from

fully manual operations to very advanced manufacturing systems [Coldwell et al. 2009]. In these systems, various robots are used mainly for picking and placing operations such as food handling, packing, palletizing, and food serving [Iqbal et al. 2017]. In addition to this, different control strategies are implemented, such as adaptive, intelligent or fuzzy logic controllers [Kondakci and Zhou 2017].

Despite the automation level, the food industry faces scheduling problems, which can also be found in almost any industrial production facility [Harjunkoski et al. 2014]. Scheduling is defined as the decision-making process that

considers allocating limited resources to tasks over given periods [Branke et al. 2016, Pinedo 2012]. Representation of scheduling problems has three fields: type of problem, constraints, and performance measures [Graham et al. 1979]. As indicated in [Fuchigami and Rangel 2018], there are multiple papers concerning, among others, job shop, flow shop, single machine, and parallel machine problems. Tardiness, makespan, production costs, lateness, and flow time are mostly considered minimization criteria. Also, heuristics, genetic algorithms, computational simulations, and mixed-integer linear programming are used. In the food industry, the flow shop problem is investigated for canned fruit factories (eg [Parthanadee and Buddhakulsomsiri 2010]), bakery production (e.g. [Hecker et al. 2014]), and dairy production (e.g. [Touil et al. 2016]).

A sugar factory can be classified as a simplified make-and-pack production system in which one intermediate product (sugar crystals) is manufactured in the make phase and is packed into different formats in the packing phase. To our knowledge, almost all papers concerning sugar production are focused on the making stage. There are articles that focus on selected operations of sugar manufacturing [Tabriz 2016], energy analysis [Taner et al. 2018], life cycle assessment [Chauhan et al. 2011], sustainability issues [Eggleston and Lima 2015] and operators' training [Merino et al. 2006]. The

packing phase is considered only by Pytlak [2014], where the authors' primary objective in the scheduling problem was to minimize the time truck drivers spent at the sugar mill.

Additionally, in the analyzed literature, publications focusing on the types of enterprises with special system characteristics were not found. The special characteristics of the system that exist in many enterprises rely on the simultaneous occurrence of a variable input stream, scheduling of processes, and the reliability of machines. It influences, among others, the efficiency of the entire enterprise.

Following the above considerations and due to the variability of the input parameters, one possible solution is to implement the Digital Twin concept to support the decision-making processes of sugar factory production. DT is a virtual representation of a real process, which enables the detection and elimination of errors in the virtual system before they appear in the real process [Chen et al. 2013]. This is possible thanks to feedback information. DT uses real-time data from the real process. Thanks to artificial intelligence, cloud computing or machine learning, the analyzed data allows for a virtual representation of the production process [Tao et al. 2019]. Digital Twin can be used in the field of logistics and production in many situations. Fig. 1 highlights sample application areas of the DT in an enterprise.

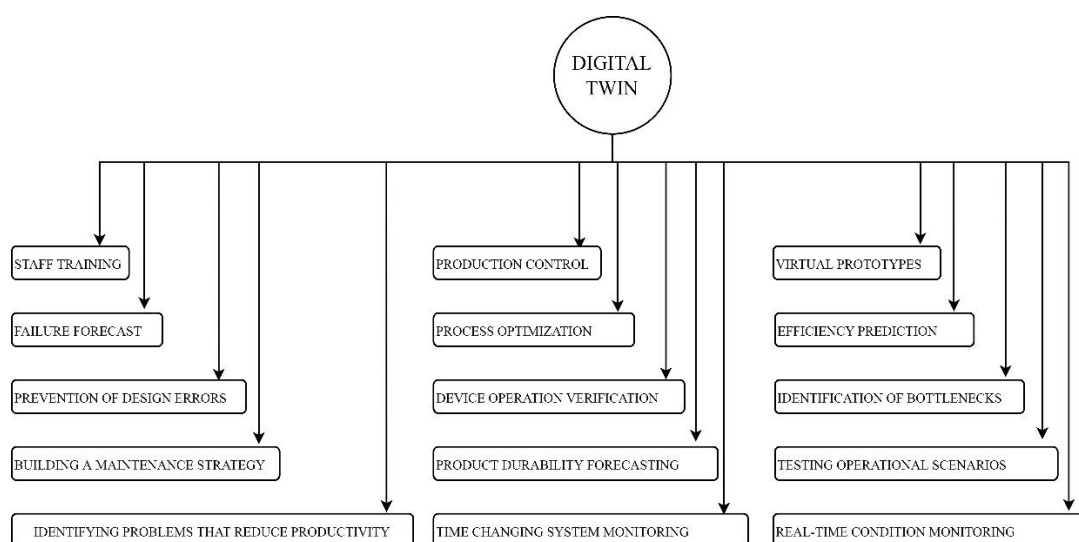


Fig. 1. Sample application areas of the Digital Twin concept in manufacturing companies.

Source: Own work based on [Errandonea et al. 2020, Liu et al. 2021, Tao et al. 2017, VanDerHorn and Mahadevan 2021]

The implementation of Digital Twins brings many benefits for enterprises, like monitoring the operation of the logistics chain, increasing efficiency, time, and cost savings, and reducing the risk of design errors thanks to the possibility of unlimited testing of operational prototypes in virtual reality. In the maintenance sector, using DT, it is possible to anticipate potential failures before they occur, improve processes, and thus create a more efficient organization. The analyzed scientific articles in the field of Digital Twin in internal logistics concern the modelling of challenging production aspects - supporting supply chain management through data monitoring (see, e.g. [Souza et al. 2019]), assistance in data structuring and machine management (see, e.g. [Olivotti et al. 2019]), supporting the life cycle of machines (see, e.g. [Konstantinov et al. 2017]), supporting the educational process of flexible production systems (see, e.g. [Toivonen et al. 2018]), optimizing planning (see, e.g. [Yao et al. 2018]), object recognition (see, e.g. [Um et al. 2018]), or supporting decision-making concerning system design (see, e.g. [Zhang et al. 2017]). However, for these models to be of the highest level, external factors such as supply chains and internal factors should be considered - employee skills and device failures.

As a result, the purpose of this publication is twofold, considering the main problems regarding the final sugar production stage. First, the authors focused on sequence determination of the stream-splitting machine, taking into account the impact of the reliability of the logistics system on system performance. The problem concerns the final stage of sugar production, where parallel packing lines share one resource with sequence-independent setup time. Determining the sequence (scheduling) is of great importance in the period of increased sugar demand, when all packing lines are utilized.

Second, the concept of implementing Digital Twin in the analyzed production processes is presented to improve the decision-making processes in the investigated case company. The possibility of connecting the Digital Twin system with the physical system is

also investigated. The developed concept allows for an examination of the effect of variable parameters on efficiency, availability, and real-time system utilization.

Therefore, in the next section, the sugar production process is introduced. On the basis of the presented description, the description of the investigated problem is provided, and the modelling approach is presented. The simulation model of the sugar packaging process is presented, together with the analyzed scheduling scenarios and the results of the case studies. The results obtained provide the implementation possibilities of the basis for investigating the Digital Twin concept. There are also identified system limitations to be overcome during the development of the DT solution. Conclusions finish the paper.

## SUGAR PRODUCTION PROCESS

Sugar production can generally be described as a three-stage process (Fig. 2), where beet processing, juice processing, and sugar processing can be observed. These three highlighted stages are related to the type of input material, which changes due to various physicochemical processes. A detailed description of every stage is presented below:

### Stage I. Sugar beet processing [Tabriz 2016]

The sugar beets delivered to the factory are being washed to remove dirt from the harvest. Then they are sliced into so-called cossettes, V-shaped pieces, which help to maximize sugar extraction. Cossettes are transported to a diffuser, where raw juice is extracted from them due to leaching. The remaining beet pulp is pressed, dried and used for animal feed. After extraction, the final process of sugar beet processing, the raw juice becomes the new input material for the subsequent processes.

### Stage II. Juice processing [Azizi et al. 2016, Urbaniec 2004]

Raw juice extracted from cossettes contains non-sucrose and unwanted chemicals from the extraction process. Because of this, purification must be executed. As a part of this, processes

such as liming, carbonation, and filtering are carried out. After purification, the juice with changed composition is called a thin juice.

Evaporation is an intermediate step between purification and the final process of juice processing. The thin juice is transported to a multistage evaporator station, where the thin juice is concentrated into thick juice in the form of syrup. Then this thick juice goes through several steps in the crystallization process. Sugar crystals are separated by centrifuging. The

remaining syrup (side product) is called molasses.

### Stage III. Sugar processing [Acebes et al. 2019]

Sugar crystals separated in juice processing must be dried and cooled before storage and packing. Usually, rotary or fluidized-bed driers are used. The dried and cooled sugar is stored in silos. Then it is packed in various packaging (e.g. large bags).

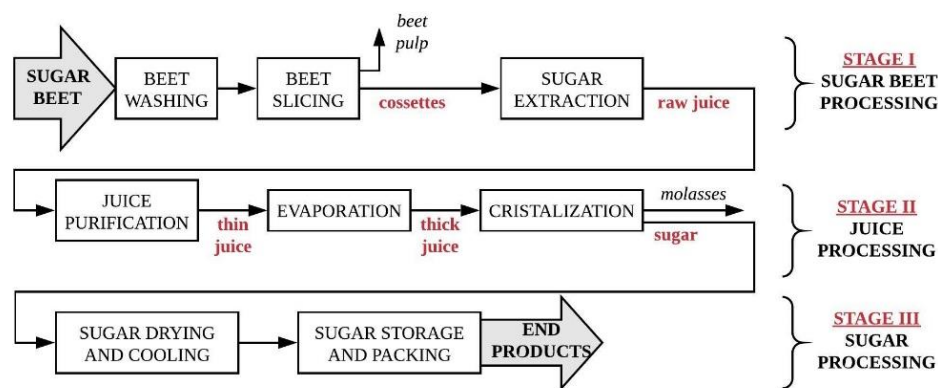


Fig. 2. Sugar production process.  
Source: Own work

Sugar production can be classified as a simplified type of make-and-pack production. Make-and-pack production systems are characterized by the make stage, where manufacturing of different intermediates takes place, and the subsequent packing stage, in which those intermediates are packed in different formats [Baumann and Trautmann 2013, Mendez and Cerda 2002, Entrup et al. 2005]. In the case of sugar production, a similar division

into make and packaging phases can be noticed. Stages I and II can be classified as the make phase, where an intermediate product (sugar stream) is formed. This intermediate product is sent to different packaging lines during Stage III, the packaging phase.

The authors focused on the final Stage III processes of sugar production, where the sugar stream is divided into different packing lines (Fig. 3).

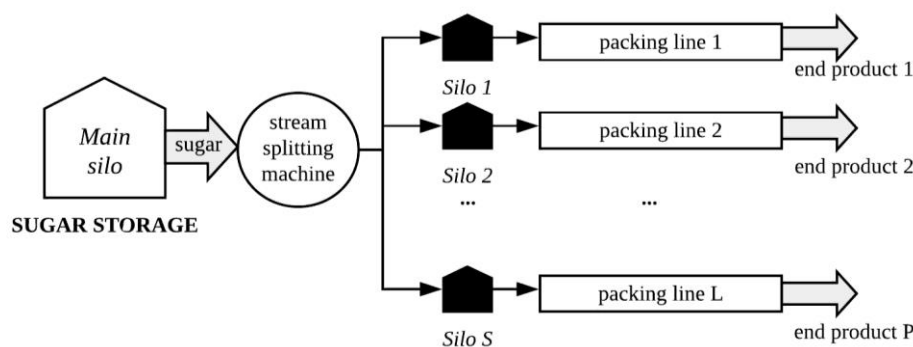


Fig. 3. Sugar storage and packing.  
Source: Own work

The stream consisting of dried and cooled white sugar crystals is transported to the main silo, where it is stored. Later, with conveyors, it is transported to different packaging lines, characterized by different efficiencies. Additionally, each line has its own silo with limited capacity and different replenishment demand times. Only one silo at a time can be filled due to the use of the stream-splitting machine.

## DESCRIPTION OF THE PROBLEM

As mentioned in Section 2, assigning produced sugar streams to different packing lines can be classified as a sequencing and scheduling problem in the simplified make-and-pack production system. This work addresses this problem and the impact of the reliability of the logistics system on system performance. We try to find the best possible sequence for the stream-splitting machine in the considered case study to minimize the inactivity of every packing line, which can occur due to the lack of material. The idle time affects the machines' reliability of the machines on this line. If there is no material in the silo at the packaging line, the sugar still left in the machines starts to caramelize. As a result, the machines should be completely cleaned of caramelized sugar before restarting the packaging process after the silo is full. The longer the idle time is produced, the more caramelized sugar is created, thus the longer the downstate time.

The problem considered in this work can be formally stated as follows.

### Given:

$l$  – the number of packing lines operating in parallel

$e_{ii}$  – the  $i$ -th packing line theoretical efficiency in tons per hour,  $i \in \{1, 2, \dots, l\}$

$e_i$  – the  $i$ -th packing line real efficiency in tons,  $i \in \{1, 2, \dots, l\}$

$T$  – the scheduling time horizon in hours

$S_i$  – the stream splitting machine setup time (sequence-independent) in seconds

$C_{imax}$  – the  $i$ -th silo maximum capacity at packing line  $i$  in tons,  $i \in \{1, 2, \dots, l\}$

$C_{icurr}$  – the  $i$ -th silo current capacity at packing line  $i$  in tons,  $i \in \{1, 2, \dots, l\}$

chosen dispatching rules

### Determine:

The replenishment sequence controlled by a stream-splitting machine

$E$  – system's efficiency in tons

## DESCRIPTION OF THE MODELLING APPROACH

The sugar packing system can generally be described as the operation of two subsystems. The first is a subsystem that supplies sugar to a splitting machine, including the machine itself. The second one is a subsystem of packing lines. Fig. 4 presents the operation scheme of the simulation model designed to analyze the problem discussed. In pool one, there is a description of the line operation before approaching the splitting machine. In the remaining pools, there is a description of individual lines.

To identify the best sequence for setting the splitting machine, it is necessary to study the real efficiency  $e_i$ . In this paper, it was assumed that it could be determined based on the following:

$$e_i = kg(t)_i * e_{ti} * t_{ai} \quad (1)$$

where:

$e_i$  –  $i$ -th line efficiency;

$kg(t)_i$  –  $i$ -th line availability;

$e_{ti}$  –  $i$ -th theoretical line efficiency;

$t_{ai}$  – availability time of sugar for the  $i$ -th line.



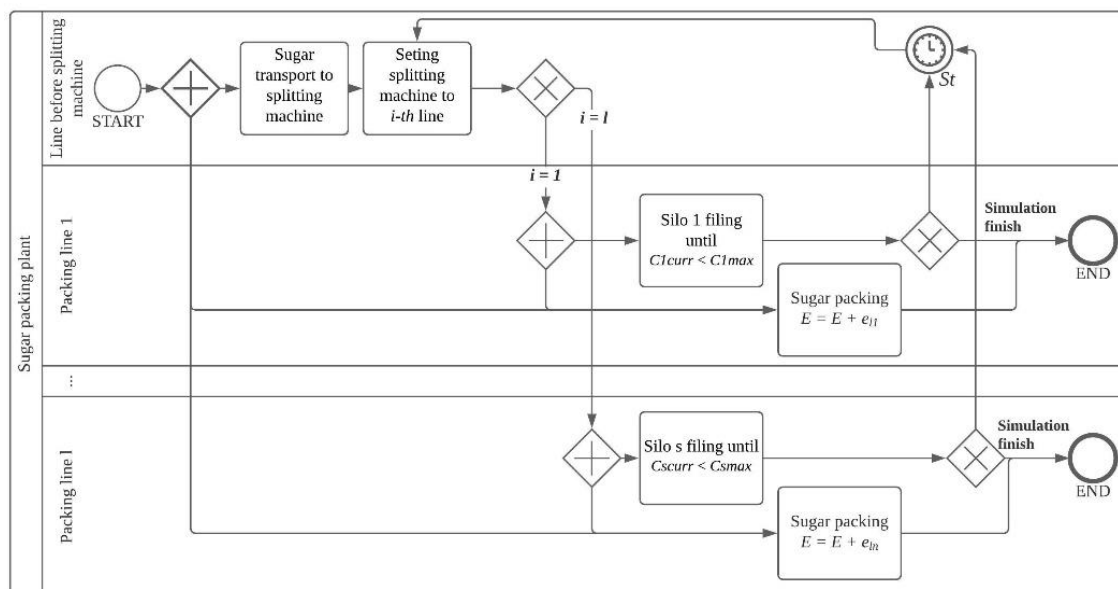


Fig. 4. Sugar packing simulation model algorithm in BPMN notation.

Source: Own work

## CASE STUDY RESULTS

Data from a real sugar factory consisting of four packaging lines were used to verify the described method to determine the effectiveness of the sugar packaging system. Table 1 shows the volume of the silos (preceding the lines) and the capacity of each line, the capacity of the line

upstream of the splitting machine, and the setup time of the splitter machine. The failures were inflicted on the cumulative distribution function for an exponential distribution  $1 - e^{-\lambda x}$ , where  $\lambda = \frac{1}{3600}$ , and the variable  $x$  is the lack of sugar time in the silo. The repair time is given with a normal distribution with an average  $\bar{x} = 1800$ s and standard deviation  $\sigma = 600$ s.

Table 1. Real system data used in the model

Parameter's name	Symbol	Value for scenario
The efficiency of the line before splitting the machine	$E_l$	65 t/h
The stream splitting machine setup time	$S_l$	141 s
Packing line 1 theoretical efficiency	$e_{11}$	3.8 t/h
Packing line 2 theoretical efficiency	$e_{12}$	15.0 t/h
Packing line 3 theoretical efficiency	$e_{13}$	10.0 t/h
Packing line 4 theoretical efficiency	$e_{14}$	17.0 t/h
Silo #1 capacity	$C_{1max}$	8 t
Silo #2 capacity	$C_{2max}$	8 t
Silo #3 capacity	$C_{3max}$	8 t
Silo #4 capacity	$C_{4max}$	8 t

Source: Own work

The level of utilization of the packaging lines depending on the sugar input stream before

the split into the individual lines is shown in Fig. 5.

It can be seen (Fig. 5) that with the input stream size from 5 to 25 t/h, only the  $e_{14}$  packing line has a higher utilization. This is mainly due to the reduced utilization of the other lines. The other packaging lines use less than 50% of their level of capacity; however, their utilization

increases from 15 t/h of the input stream. Increasing this stream above 35 t/h will not have a significant impact on the utilization of the  $e_{11}$  line. For all lines to be used to the highest degree, the input stream in the described case should be 65 t/h.

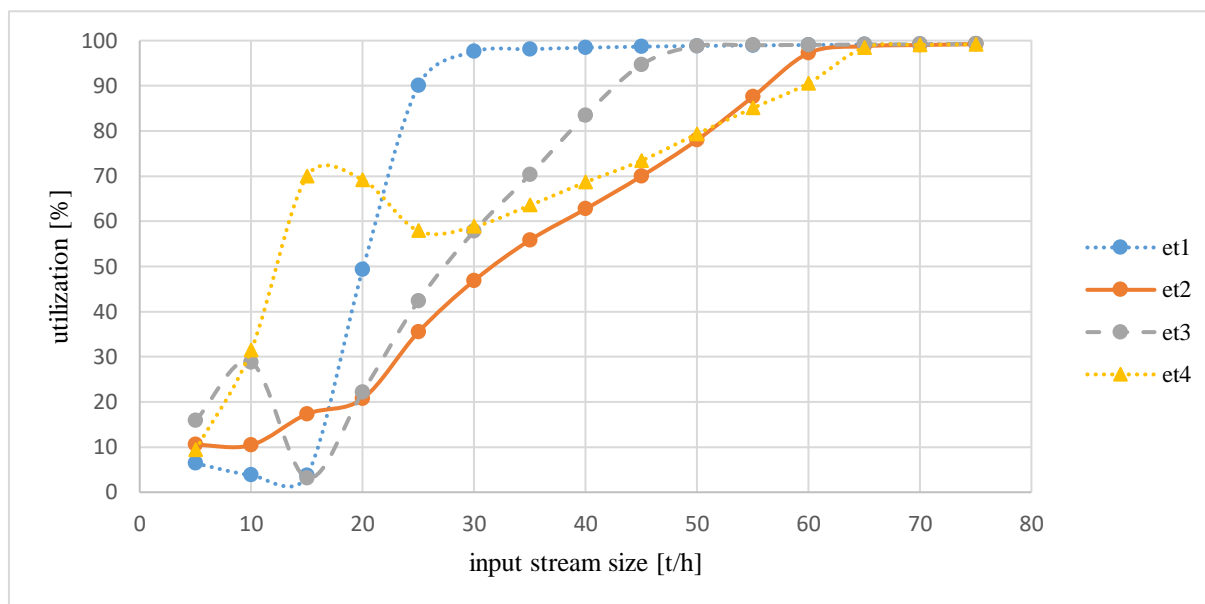


Fig. 5. Utilization of packaging lines depending on the input stream size.

Source: Own work

Another interesting aspect is an analysis of the availability of packing lines depending on the input stream size before sugar is split into the individual lines (Fig. 6). It can be seen that line  $e_{14}$  obtains 100% availability regardless of the input stream size. It means that with the indicated silo capacity and line efficiency, sugar is constantly present in this silo or the lack of sugar time is so short that the sugar does not caramelize in the machines. The availability of the remaining lines decreases when the input stream size is 20 to 25 t/h. This means that this input stream size is too small for all lines to have continuous access to sugar in the silos. As the size of the sugar input stream increases, the availability also increases. All packaging lines achieve maximum operational availability with an input stream size equal to 65 t/h.

The sequence arrangement between four lines was analyzed in the case presented. Therefore, 24 sequences were considered to include all possible sequences of filling the silos. It was assumed that all silos were empty at the

beginning of the simulation. The simulation starts with backfilling the first silo, depending on the scenario (scheduling). Twenty-four hours of packing line operation were simulated. Two scenarios were analyzed - one with the lowest and one with the highest overall average system efficiency. The aim was to assess the influence of the the selected sequence of sugar splitting machine on the system efficiency. The average amount of sugar produced for the entire system is 1085.79t, with a standard deviation of 0.66t. The divergence in the amount of sugar packed sugar in the system between the two scenarios analyzed scenarios equals 2.572t. For each packaging line, a different scenario is the most efficient. Indeed, those scenarios which show the highest and the lowest average system efficiency. Therefore, none of the packaging lines reached their maximum efficiency in the scenarios analyzed. The efficiency of the scenarios analyzed in tones is presented in Table 2. Table 3 shows the percentage efficiency of the scenarios analyzed.

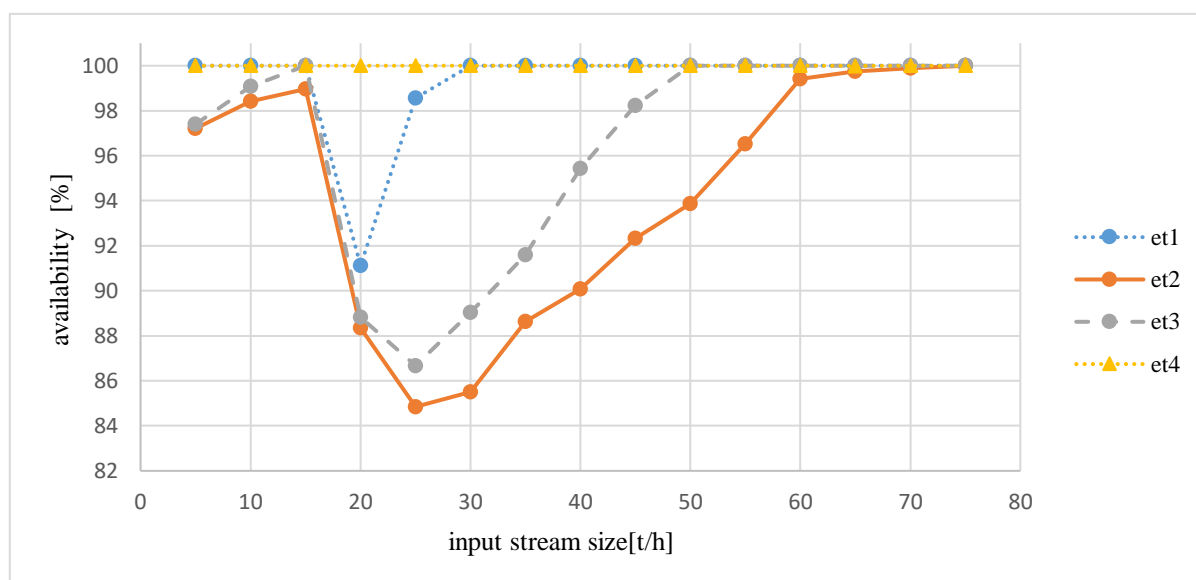


Fig. 6. Availability of packaging lines depending on input stream size.

Source: Own work

Table 2. The efficiency of the analyzed scenarios in tones

	Packing line 1	Packing line 2	Packing line 3	Packing line 4	System
Average efficiency Scenario 1 [t]	90.68	356.94	237.30	399.39	1084.31
Average efficiency Scenario 2 [t]	90.15	354.00	238.50	404.23	1086.88

Source: Own work

Table 3. The percentage efficiency of the analyzed scenarios

	Packing line 1	Packing line 2	Packing line 3	Packing line 4	System
Average efficiency Scenario 1 [%]	99.39	99.66	98.88	98.74	99.1675
Average efficiency Scenario 2 [%]	98.82	98.84	99.38	99.94	99.245

Source: Own work

The time it took to run one simulation in the case studied was also measured. For the analyzed case, it lasts approximately 10s. This time is mainly influenced by the parameters of the computer on which the simulations are carried out. However, it does not change the fact that it is possible to obtain information that allows for the selection of an appropriate scenario in a short time.

The developed model does not take into account downtime resulting from failures of system components. Such a system is influenced by many factors, including input stream size, the number of failures, the size of the silo backfilling

stream, packing process time, machinery reliability, and transport arrival time. When scheduling is predicted, only the current state is taken into account, and any introduction of changes requires the design of a new model and subsequent simulations to determine the best new scheduling sequence.

In order to respond in real-time to emerging changes, it is necessary to automate the system by applying the Digital Twin concept. Through the application of this concept, past, present, and future behaviour will be presented and estimated in a short period, which can help in action planning.



The process of implementing the Digital Twin concept in an enterprise is based on five basic implementation stages presented in Fig. 7. The main issue is to identify the intended results

and reliable mapping of the physical system in a virtual representation so that the obtained results are at the highest level of accuracy.

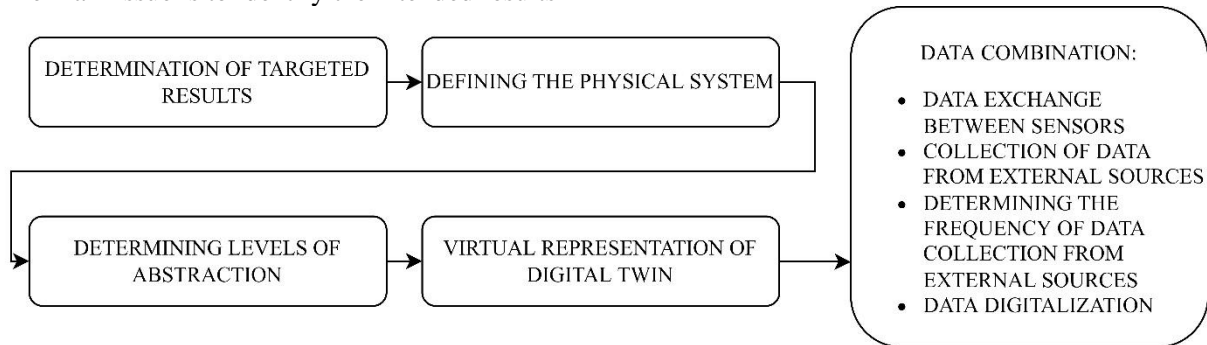


Fig. 7. Implementation stages of Digital Twin concept in an enterprise.

Source: Own work

Using DT, it is also possible to present the results of simulations, which are used for decision-making on subsequent actions. The designed system is modelled with a multilevel approach; high-level details are considered. The database is based on information from sensors and other historical sources - repair reports, failure history, transport arrival time, etc. With the help of the sensors used, information on the

sugar content level in the silos, the machines' operating status, and employees' operating status is provided. The input of data from various sources enables better production planning and control. In DT, the data flow is fully automatic. The database is designed to simulate the process in virtual reality, and the best solution can be implemented in the actual process using artificial intelligence and machine learning techniques. The concept of Digital Twin operation is presented in Figure 8.

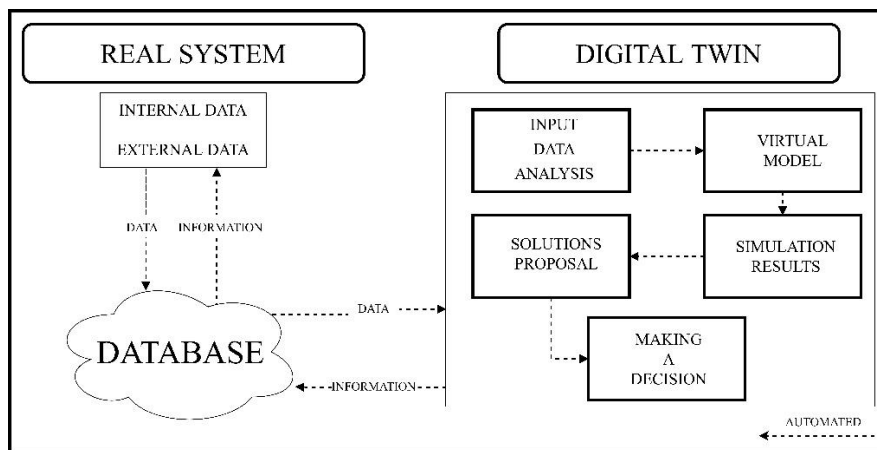


Fig. 8. The concept of Digital Twin operation.

Source: Own work based on [Bestjak and Lindqvist 2020, Rodic 2017]

The company studied was analyzed regarding the possibility of implementing the DT concept. Following the literature, enterprises may face the limitations of the current system.

Based on [31] there were developed limitations that may occur during the implementation of the DT concept in every company (Table 4). These technical limitations can be overcome by eliminating them by developing the enterprise or changing the infrastructure.

Table 4. System limitations on implementing Digital Twin in a company

SYSTEM LIMITATIONS ON IMPLEMENTING DIGITAL TWIN	
<b>TERMINOLOGY</b>	common terminology in different data sources to prevent misunderstandings
<b>DATA QUALITY</b>	systematic data download, completeness and accuracy of data, striving to minimize measurement errors
<b>CONNECTIONS</b>	real-time constant data exchange with the physical object and improved network connections to facilitate data transfer
<b>DATA SHARING</b>	sharing data among cooperating units
<b>AUTOMATION</b>	automation of data exchange and analysis
<b>TECHNOLOGY DEVELOPMENT</b>	the combination of technologies under development hinders the evolution of DT and increases the risk of implementation failure (3D simulations, Internet of Things, artificial intelligence, Big Data, machine learning, cloud computing)
<b>COMPUTATIONAL MODELS</b>	increasing the accuracy of models
<b>DATA VISUALIZATION</b>	presentation of results in a way that supports decision-making
<b>REAL-TIME RESPONSE</b>	Digital Twin responding with relatively low delay
<b>COSTS</b>	high costs related to the implementation, incl. IT infrastructure, sensor system,
<b>TIME</b>	Digital Twin implementation is a time-consuming and labour-intensive operation due to the development of computer models with high fidelity, their simulation and integration of the technologies used
<b>SECURITY</b>	data management with regard to ensuring their security and intellectual property rights
<b>REPRESENTATION</b>	the accuracy of the representation of real processes in virtual space is very important

Source: Own work based on [Kosior 2020, Singh et al. 2021, Sing et al. 2018, Tao et al. 2018, VanDerHorn et al. 2021]

Based on the summary presented (Table 4), the main implementation limitations were identified in the company were identified. A problem has been noticed in the connection, data quality, and sharing areas. DT requires real-time input data from the physical object because they are used to update model parameters and make ongoing engineering decisions continuously. Analyzing the data in the system, one can see a situation in which a machine splitting sugar stream between the various silos at the packaging lines performs two activities simultaneously: at the end of the silo backfilling state and in the silo changing state. In real life, it is impossible for the machine to be in two states simultaneously. Abnormalities cause this event in the operation of the silo sugar monitoring system. This malfunction causes a delay in data download, which is around 65s in the analyzed system. For the implementation and efficient use of the Digital Twin in the make-and-pack system, it is necessary to improve the synchronization of sensors with the system so that the data is

downloaded in real-time without delay. These delays may be caused by an inadequate connection or incorrect selection of the cooperating devices. Due to the continuous development of sensors and technologies used in Digital Twin (IoT, Big Data, machine learning, etc.), it is necessary to adapt the devices used to the current system. It is also recommended to follow trends and news in this area. It is also necessary to improve the exchange of information with the transport company, to keep track of the arrival time of vehicles.

## CONCLUSIVE REMARKS

This paper presents results for sequencing and planning of packaging line problems. The modelling approach was based on conducting simulation experiments. Therefore, the results obtained can be used to optimize case-company production processes.

The strategy selection is essential when the sum of the line efficiency is greater than the line

efficiency before the splitting machine. The higher the total efficiency of the packaging lines, the closer the real efficiency to the theoretical one (the real efficiency is a result of the amount of sugar supplied to the system). However, the calculations carried out in Section 5 indicate that even a slight change in the input parameters can completely change the optimal solution. Therefore, each time it is required to build a model and modify the variables, they correspond to reality and then calibrate the system settings according to them. This confirms the rightness of using Digital Twin for scheduling, considering the variability of internal and external factors. However, there remains an open question regarding downloading up-to-date data from the real system.

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