Design and development of a Digital Twin for a production line: a case study from the winter-sport sector

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Abstract: The increasing complexity of products and manufacturing processes, combined with the increasingly advanced technological integration of the manufacturing sector, raised new challenges for world-class industries to optimize time-to-market, resources and cost. Simulation, as a key Industry 4.0 enabling technology, allows to emulate the steps of a manufacturing process, thereby achieving significant improvements in all the phases of the product and process development. A simulation model supports the design and sizing of the production plant, in order to ensure the correct functionality of a line, checking for any criticalities before its inclusion in a process; the improvement of existing processes, identifying problems that may induce bottlenecks; the verification of cycle times; the optimization of production KPIs, the testing different scenarios and the effective planning and scheduling of daily production. A simulation process can be implemented and improved by creating the Digital Twin of the industrial system, which can be realized on a single line scale or extended to the whole factory. Its intention is to replicate every function and operation of interest within the company. Furthermore, through the integration with the management and control systems (MES, ERP, WMS), it is possible to connect the virtual model to the physical environment to obtain real-time data exchange. This paper follows this outline and shows the design and development of the digital twin of a production line for hockey balls present in the Smart Factory of Ostschweizer Fachhochschule. The entire production process is reproduced using Siemens Technomatix software, while Siemens MindSphere software is used for the data connection feeding the Digital Twin with data from the physical operative environment.

Keywords: Industry 4.0, Digital Twin, optimization.

I. INTRODUCTION

Industry 4.0 is the fusion of the current production technologies with innovations from the world of IT, information and communication. Industry 4.0 represents a transition of production paradigms by transforming the current system into a more flexible and adaptable one, with the ability to learn and make autonomous decisions. After the steam engine, the assembly line and automation, industry 4.0 is often considered the fourth industrial revolution [1,2]. Since the first industrial revolution of the 18th century, the world has faced the challenge of producing an increasing number of goods from finite and depleting natural resources to satisfy the ever-increasing demand for consumption, while minimizing negative environmental and social impacts [3,4]. A key objective of Industry 4.0 is to drive a new form of progress that excels in resource optimization, waste management and other sustainable practices. As a result, it will be possible to achieve significant improvements in production and technology, presenting new opportunities for closed-loop production, maximizing the use of previously applied resources and minimizing the extraction of raw material [5]. Most economists agree that the main feature of this period is the use of Cyber-Physical Systems (CPS) or, in other words, the linking of real objects and people with virtual objects through computer networks. This can be defined as the ability of CPS to create a virtual copy of the physical environment, providing a connection between the real and virtual system to collect data, which will have an impact on the simulation model. Process simulation throughout software is directly linked to business process improvement. Organizations can use process simulation at all levels of maturity to achieve significant benefits. Due to the continuous progression of information technology and the advancement of the fourth industrial revolution, software is replacing hardware as responsible for most of the functionality provided by systems. This increasing role of software in product development is bringing great advantages within companies in terms of cost reduction, time optimization and improved product quality. Simulation has gained importance in the past years and allows designers to imagine new systems enabling them to both quantify and observe behavior [6]. Whether the system is a production line, an operating room or an emergency-response system, simulation can be used to study and compare alternative possibilities or to troubleshoot existing systems [6,7]. Although the world of simulation is applicable to countless engineering and non-engineering fields, this paper will focus mainly on the manufacturing sector. Identifying errors in the planning phase is much cheaper for a company than doing that after the start-up of a project or its full implementation. Performing a computer simulation makes possible to assess whether the project was designed properly and is performing as expected. Simulation provides a comprehensive perception of the studied process or product, allows to conduct multi-criteria analysis, and to test many scenarios. That is why computer systems are becoming necessary tools which support the design and improvement of business processes [8]. The stages involved in the development of a simulation can be summarized in the following figure:

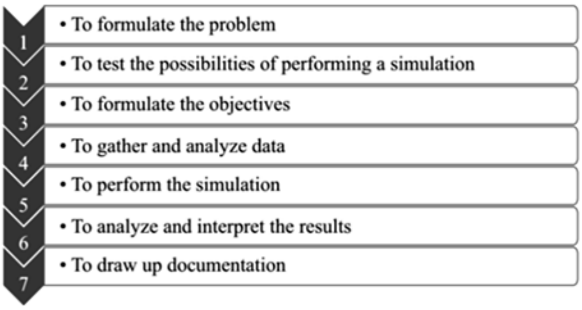


Fig. 1. The methodology of conducting simulation [8].

The simulation model recreates all operations in a virtual three-dimensional environment, giving the possibility of seeing, during the animation, human and mechanics models to perform the required tasks. Hence, in this context simulation is used as a cognitive tool. As regards the realization of the virtual model of production systems, there are normally two phases that contribute to its implementation. The first phase is the modelling operation, which can be divided into two main steps: i) generation of the plant layout, and ii) input and characterization of human models. The plant layout is normally designed using CAD software, which provides a reliable copy of the company's machinery. Following its creation, the files can be loaded into a production simulation software, thus obtaining a visually satisfactory and self-explanatory result [7]. The creation of the 3D model is very important for the second modelling phase, characterized by the insertion of human models. Without representative 3D files of the machinery, it is not possible to comprehend the size and space requirements of the workers. With this step, it is consequently possible to achieve significant improvements in employee safety by ensuring that workers have the appropriate distance between stations and/or other operators. The second step consists of inserting the production variables. These may be predefined values coming from the current configuration or can be random variables. The latter permits to simulate any problems that may occur in the production chain, such as a machine stoppage, the breakage of a tool or a missed machining operation, etc. The combination of these two steps generates a reliable model that is faithful to the real world. Following this step, it will be possible to proceed with the implementation of improvements, based on the KPIs defined by the working group. It is important to highlight that there are various types of simulation models, which are subdivided according to how information is exchanged between the real and virtual worlds. The currently existing models are the following:

1. *Digital Model*

   A digital model is described as a digital version of an existing or planned physical object. Examples of a digital model could be, but not limited to, construction plans, designs and product development. The important defining characteristic is that there is no form of automatic data exchange between the physical system and the digital one. This means that once the digital model has been created, a change made to the physical object has no impact on the digital version [10].

2. *Digital Shadow*

   A digital shadow is a digital representation of an object that has a unidirectional flow between the physical object and its digital version. A change in the state of the physical object results in a variation of the digital object and not vice versa [10].

3. *Digital Twin*

   If data streams between an existing physical object and the digital one, and the flow is fully integrated in both directions, this establishes a "Digital Twin" reference. A modification made to the physical object automatically leads to a modification in the digital object and vice versa [10].

The main objective of this project was precisely to achieve a robust data flow, streaming in either direction between the field hockey ball production line machinery installed in the Smart Factory of Ostschweizer Fachhochschule and the created digital simulative model. The implementation of the Digital Twin has permitted the construction of a solid and efficient basis not only for the availability of information, but also for the evaluation of any modifications that can be implemented on the line. The model created has enabled the analysis and potential optimization of parameters related to machinery cycle times, production layout, energy savings, as well as evaluation of the logistical stocks needed according to effective production volumes.

II. DIGITAL TWIN

Digital twin (DT) is one of the most promising enabling technologies for realizing smart manufacturing and Industry 4.0. Its emergence assumes a crucial importance in the development of industry solutions, as noticed by the Gartner hype cycle that places this technology as a trigger of emerging innovation in 2017 and at the peak of inflated expectations in 2018. Indeed, the DT concept falls under the trend of digitalized ecosystems, and Gartner expects that in the next five years, hundreds of millions of objects, machines or systems will utilize this solution. Sensors and data transmission technologies are increasingly used to collect data throughout different stages of a product’s lifecycle, including product design, manufacturing, distribution, maintenance, and recycling [2,13]. The usage of DT for performance is essential, and for capital-intensive equipment it has proven to be successful in terms of cost savings and reliability improvements. A DT is defined widely, but it is more accurately described as the smooth integration of data between a physical and a virtual machine in both directions [11,12]. The key aspects that this type of technology focuses on are presented as follows:

i. To Reduce time-to-market by interweaving simulation models across multiple levels of detail, across all involved disciplines and product life cycle phases [9].

ii. To enable description and evaluation of system behavior, observing performance and making quality considerations, providing an interface to different models and data in different granularities while keeping them consistent [9].

iii. To optimize mechatronic products and systems during their use or operation [9].

It is therefore clear that DT allows to find solutions to a large variety of industrial problems, succeeding in collecting and utilizing at its best information of different nature. These capabilities create value throughout the life cycle of industrial as-sets. The table below shows the key features and use cases of the DT.

The key to implementation of the DT is to focus on what types of information will be required during the lifecycle of the asset under consideration. It is therefore important to structure the information in a reusable way. In general, the creation of the DT encompasses two main areas of concern: designing the DT processes and information requirements in the product life cycle, from the design of the asset to the field use and maintenance of the asset in the real world; The creation of the enabling technology to integrate the physical asset and its DT for real-time flow of sensor data and operational and transactional information from the company’s core systems, as expressed in a conceptual architecture [12]. The paper describes the realization of the DT of a production line for hockey balls present in the Smart Factory of Ostschweizer Fachhochschule (OST) in Rapperswil-Jona, Switzerland [17]. The DT modeling phase has been entirely realized with the assistance of Siemens - Tecnomatix Plant Simulation software, a production simulation platform. The real-time flow was instead established through the connection of the above-mentioned software with another tool, Siemens - MindSphere Closed Loop System Simulation. The data is transmitted through sensors installed on the machinery and then collected on the cloud. The paper describes the methodology and tools adopted for the DT development and the preliminary results of process simulations.

TABLE I
DIGITAL TWIN FEATURES [14].

Feature	Functionality
Document management	All documents (drawings, instructions, etc.) associated to equipment throughout its lifecycle
Model	Digital representation of the equipment that can mimic properties and behaviors of a physical device
3D representation	Properties of a physical device (measured or simulated) mapped to a 3D digital representation
Simulation	Representation of a physical device in a simulation environment to study its behavior
Data model	Standardized data model for connectivity, analytics, and/or visualization
Visualization	Graphical representation of the object either on a supervisory or personal device
Model synchronization	Alignment of a model with real world parameters (potentially in real-time)
Connected analytics	Algorithms and computational results based on measured properties of a physical device

III. CASE STUDY DESCRIPTION

The intelligent factory built at the OST Rapperswil-Jona site includes a production line for hockey balls. Inside the line there are, respectively, a molding machine, a three-axis robotic arm, a conveyor carriage, a second seven-axis robotic arm, a three-dimensional scanner, a vertical storage, consisting of plexiglass cylinders placed vertically following a circular arrangement around the seven-axis robot, an assembly station and a storage for finished products. Inside the production line is also present a user interface of significant importance within the production process.

A. *The manufacturing process*

The whole process starts from the melting of plastic chipboard with the aid of the molding machine. Chips are manually placed inside a container. Once the machine has reached the proper temperature of pressure fusion, it is possible to produce the hockey balls halves. The color of production is decided according to the needs dictated by the warehouse: in case there is a lack of a particular color, its production proceeds. Once the molding process is over, the molding machine separates the two parts of the mold, from where it is possible to extract the manufactured product. The extraction takes place through the use of a three-axis robotic arm (X-Y-Z) equipped with a robotic handle that, thanks to a rotation, allows to extract the component from the previous machine. Once the half-balls have been extracted, they are placed on the conveyor from which two different storing configurations can be obtained:

1. Operator storage. The half-balls fall directly from the conveyor into a box at the end of it. The products are then collected in a warehouse outside the line. This operation can be conducted in order to have more half-balls available than the number that can be contained in the vertical storage located above the seven-axis robot (limited).
2. Robot storage. Half-balls are stopped by the conveyer at a specific location at the end of it. From here the seven-axis robot can pick them up directly.

In case of robotized storing, after the pick-up, the robot places the half-balls in an intermediate station that consists of a 3D scanner. This operation could also be carried out manually through the use of an external operator. The purpose of the scan is to collect data related to a specific production batch. It is possible to have information regarding the surface of the finished product. Once the scanning is complete, the robot places the balls in the vertical storage, where they are sorted according to color. The information for the correct storing of the parts comes directly from the molding machine: when a specific color is produced, this information is entered into the shared database. Automatically the robot will know in which store it must place the half-balls. Once the batch storing is finished, the robot waits to receive an order from the user interface. Through a user interface consisting of a touch screen, it is possible to order the ball. By selecting the various colors and clicking on the order button, the customer will receive a ticket on which is printed a QR code corresponding to the order placed. Thus, the assembly phase begins: The robot removes the selected color half-balls from the vertical store and places them in an assembly station. Here the half-balls are held by a locking system with the inner sides facing each other. The assembly is carried out by a plate of conductive material which, once heated, intervenes between the two halves. The half-balls are then placed close to the plate and are kept in this position for a sufficient amount of time to melt the plastic surface. Then, the halves are separated and the plate is removed. The machine can now proceed to the realization of the finished product which consists in the union of the two halves. Once the assembly phase is complete, the ball falls into a slide that places it in a circular store, which can be equated to a sort of circular carousel. The product will remain in the store until the order is redeemed by the user. This is accomplished by presenting the ticket obtained from the order to a QR code reader. At this point it will be possible to collect the ordered product. Tecnomatix Plant Simulation (TPS) has been used to simulate the hockey balls production line. TPS is an object-oriented 3D program used to simulate discrete events, which allows to create realistic, digital logistic systems (e.g. production) and thus test the properties of the systems and optimize their performance. The software features advanced analytical tools, such as bottleneck analysis, statistics and charts, which are very useful when analyzing different production scenarios. The results provide information needed to quickly make good decisions in the early stages of production planning. In addition, it enables the optimization of material flow, resource utilization and logistics at every planning level from global production facilities, through local companies, to individual lines [8]. The software features a modeling platform with which a manufacturing plant can be simulated in 2D or 3D. Regarding the modelling phase, it is possible to utilize some preset elements included in the software itself. In fact, stations, robots, workers, conveyors, parts etc. are provided, thanks to which it is possible to obtain satisfactory simulations from the point of view of the results. In order to analyze with precision also the space management, the safety, efficiency and comfort of working environments, TPS offers the possibility to import graphic models coming from Siemens's software or from third parties. In addition, operational and design aspects of a wide range of human factors can be tested, such as injury risk, timing, worker comfort, availability, field of view, energy use, fatigue limits, and other important parameters. Through a dedicated section in the attribute definition of each station, it is possible to extend the contingencies to equipment units too. Based on real failure and blockage data, improvements can be achieved from a predictive maintenance point of view, but it is also possible to accurately estimate the number of products that can be produced depending on the discontinuity of the stations. In addition to logistics and material flow, it is also possible to obtain from the simulation information about the energy consumption of the line, obviously extendable to the entire factory. Indeed, TPS includes an integrated energy analyzer that shows current, maximum and total energy consumption. There is an integrated energy plotter on the platform that dynamically displays energy consumption during the simulation, allowing to see energy usage both during working time and during scheduled breaks. TPS has been coupled with Siemens MindSphere (SMS). SMS is Siemens' open, cloud-based Internet of Things (IoT) operating system provided as Platform as a Service (Paas) that enables the connection of real things to the digital world and allows the creation of powerful industrial applications and digital services. Through the use of artificial intelligence and real-time data collection, the software enables to achieve significant improvements in terms of optimization, savings and enhancement of the entire product life cycle management (PLM). The main features of this technology type are:

i. Linking system simulation models with onboard resources.
ii. Managing simulation model and simulation model parameter configurations by requesting operational data.
iii. The possibility to acquire operational data from assets on board for any period of time and configuration.
iv. The opportunity to create simulations using operational data for system analysis.

SMS uses secure end-to-end technology to connect devices and pass data through. Using the MindConnect API (application programming interface), it is possible to effectively connect with all IoT-ready assets from any manufacturer. The software provides a flexible way to connect multiple data systems to SMS, including historian databases from enterprise resource planning (ERP), manufacturing execution system (MES) and supervisory control and data acquisition (SCADA) systems. The exchange of data between the real world and the virtual one has been possible through the use of the plug-in of SMS, called Closed-Loop Foundation. This application provides a basis for connecting several applications, including TPS, with SMS. The closed-loop MindSphere Foundation offers a mechanism to map the virtual model with the physical model and apply it consistently to different domains such as product and production [18].

IV. Digital Twin design

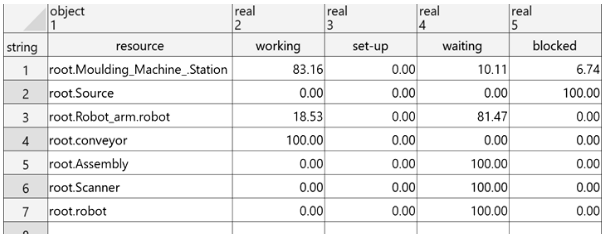
The purpose of the DT's development of the field field hockey ball production line was to obtain reliable data by analyzing different production scenarios. It is therefore possible to identify as KPIs of the project the analysis of the occupation of the various stores (vertical store positioned above the seven-axis robot and external warehouse) and the analysis of the production times of each machine, evaluating different methods of production and storage. The data collected therefore consist of the working times of each station and the number of half-balls that can be stored inside the vertical stores, assuming for simplicity that the number of half-balls containable inside the collector positioned at the end of the conveyor was almost unlimited, considering that an operator can intervene to replace it whenever the collector is about to reach its maximum capacity. The implementation of the simulation has begun with the realization of a simplified simulation, using only the stations and the internal components of TPS. This has been made to develop with rapidity a simulation that could summarize all the necessary passages to the realization of the finished product and for taking confidence with the software. Consequently, it was necessary to proceed to the insertion of the real geometries and the animation of each station. The 3D files of the various stations were integrated in the model. The graphical structure of the 3D file was recognized by the program as a single identity, on which it would not be possible to apply changes to individual stations. Therefore, it was necessary to divide the macro into all the various sub-stations. The process of splitting and converting 3D files started from the molding machine. Once completed, it was necessary to define the functions that govern the station, known internally in the software as “*Method*”. The creation of these objects took up a large part of the research activity, as their proper design defines the correct functioning of the simulation. In particular, these objects were used within the simulation to:

1. Defining the movements of animated parts.
2. Setting the correct station process times.
3. Defining the correct iterations between stations (release of processed products, selecting a production process, etc.).
4. Designing the user interface, sensors and defining the attributes of the various stations.

Proceeding with this methodology, by using the provided and collected data and following the project specifications, the whole simulation was developed.

V. Results and Discussion

The resulting model closely follows the physical model present in the OST laboratories. From a simulation point of view, it allows all possible production scenarios to be analyzed, guaranteeing easy availability of production data (machine times, store occupancy, machine use). The model enables not only the production of half-balls to be simulated, but also the ordering of the finished product through the design of a user interface. This gives the opportunity, by implementing a random order generator, to analyze the behavior of the system in a complete operating situation, from which it will be possible to obtain information on potential improvements to be applied in the line, also evaluating the replacement or a different configuration of the machinery in order to meet customer demand. The "Bottleneck Analyzer" tool (Fig. 2) facilitates the analysis of trends in the utilization of the corresponding stages.



	object 1	real 2	real 3	real 4	real 5
string	resource	working	set-up	waiting	blocked
1	root.Moulding_Machine_.Station	83.16	0.00	10.11	6.74
2	root.Source	0.00	0.00	0.00	100.00
3	root.Robot_arm.robot	18.53	0.00	81.47	0.00
4	root.conveyor	100.00	0.00	0.00	0.00
5	root.Assembly	0.00	0.00	100.00	0.00
6	root.Scanner	0.00	0.00	100.00	0.00
7	root.robot	0.00	0.00	100.00	0.00

Fig. 2. Bottleneck Analyzer result following the production of 20 half-balls with storage via Drain.

Thanks to this feature, it is possible to immediately optimize machine times (downtime, production, setup, etc.) by testing different configurations through simulation. Thanks to the data flow from the machines channeled through SMS, real production data can be used. Since, by DT's definition, data flows in both directions, a modification on the virtual application will ensure a modification on the physical model, thus enabling precise production changes to be made according to requirements. The simulation model appears as in Fig. 3.

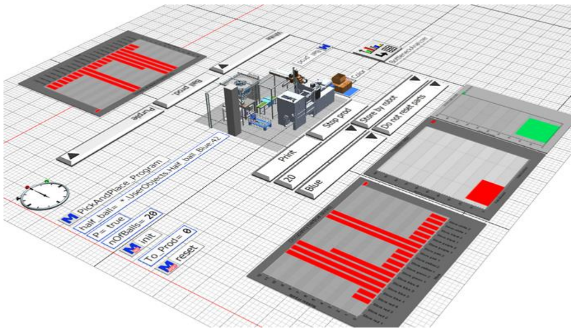


Fig. 3. Final result of DT modelling.

In terms of production, the most significant parameters, variables through the simulation model, are definitely machine times, which can be expressed as the speed of commands execution of stations (speed of electric motors of robots, die-cutting times). From the perspective of mass production, the simulation of different scenarios offers the possibility of performing logistical evaluations according to the variation in market request: assuming an increase of demand, it will be possible to estimate whether the current configuration of machinery guarantees the planned production batch and to estimate the right cadence of raw material purchases, based on the consumption detected by the simulation. By using data from SMS, it was also possible to collect and analyze information about the consumption of each station throughout the execution of a process. As can be seen from Fig. 4, energy consumption varies considerably during the injection phase for the molding station.

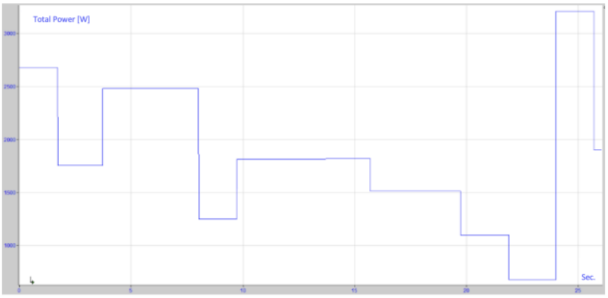


Fig. 4. Energy consumption of the molding station throughout the process, collected via SMS.

The variation is explained by the usage of different electric motors in the respective steps, as well as the heating of the plastic chips for the injection phase. The same considerations can be made for all other stations. For example, utilizing two (or more) electric motors at the same time for the seven-axis (or three-axis) robot would inevitably result in a higher peak in energy consumption. By collecting energy data, and entering it into the simulation software, different scenarios can be analyzed to find the optimal solution that satisfies process time expectations and saves costs through lower energy consumption. Optimization of energy consumption ensures lower fixed costs, resulting in higher corporate profit margin. Although these improvements can be carried out quite easily on the robot stations, this is not the case for the molding machine. Besides being clearly the most energy-consuming station, its timing and its parameters are directly correlated to the quality of the finished product. Therefore, the optimization of this station should necessarily be followed by a quality test on the half-balls to verify that their characteristics meet the required standards. The procedure developed to perform the quality assessment can be summarized in the following list:

i. Carrying out multiple moldings with the current process parameters.

ii. Collect data on energy consumption, injection temperature, heating and molding times and other variables considered influential through SMS.

iii. Analyze the data (randomly to avoid any correlation) using MindSphere itself, alternatively use external analysis software, e.g. R Studio. By defining an equation for energy consumption, it is possible with the latter software to easily perform an F-Test, evaluating the influence of variables on total energy consumption. If there are many variables involved, an AIC test (using the Akaike information criterion) should also be considered in order to choose the parameters to be optimized and observe any correlation between them.

iv. After collecting the necessary considerations regarding the most influential parameters on energy consumption, it is necessary to carry out some production tests by varying these variables and to analyze the quality standards of the finished product. Again, an objective function could be defined, where the parameter to be optimized is the required quality, defined through KPIs of the finished product (e.g. hardness and elasticity).

v. Once the necessary hypotheses have been gathered, upload the information on the digital twin and analyze different scenarios according to the results obtained from the statistical and qualitative test.

vi. Since a satisfactory result has been obtained, verify the model by conducting a molding test with the chosen parameters.

vii. If the results obtained have indeed led to an improvement in energy levels, the properties of the finished product will have to be assessed. If these are satisfactory, an optimal solution has been reached, otherwise try a different configuration.

The same procedure could be carried out for the optimization of the other stations, but it will not be necessary to check the quality of the finished product. The only factor that might vary is the timing, but this can be verified faithfully using TPS. Another advantage of using cloud-based data collection is the possibility of predictive plant maintenance. In Fig. 5 an example of TPS application for bearings failure estimation is reported. This type of technology is gaining ground in Industry 4.0 and brings enormous economic benefits. Thanks to it, it will be possible to avoid unnecessary equipment replacement, save costs, improve process safety, availability, and efficiency. The data, collected through the cloud or online services, is processed by an algorithm that uses linear regression models to predict not only imminent, but also future failures within a certain probability range. This technology therefore permits the monitoring of machine failures that can normally be considered as random variables.

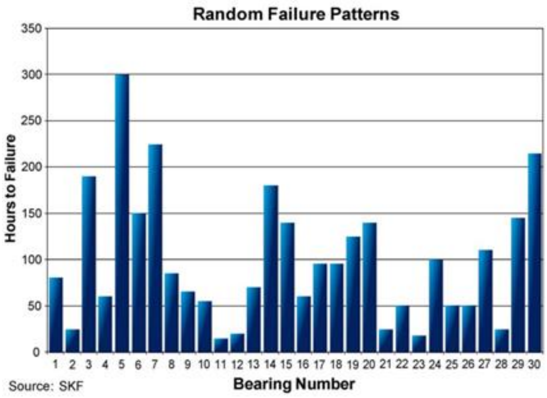


Fig. 5. Hours of work before failure under identical conditions, SKF bearings [19].

The parameters to be considered are variable and depend directly on the type of machine to be monitored. Normally, the most commonly used and applicable for a variety of applications are: vibration analysis, which can be used to assess the failure of a bearing or the unbalance of the machinery; temperature variation (thermography), usually associated with increased friction between mechanical components; acoustic signals (spectrum analysis), synonymous of the malfunctioning of mechanical components. In general, all variables that can be measured using specially designated sensors may be utilized. Assuming a predictive maintenance analysis on the injection molding machine, which is not only the most expensive but probably also the most delicate machine, the right number and type of sensors would have to be installed. In this case, it is recommend the adoption of the following types of sensors: sensors with accelerometers for vibration assessment, laser sensors for temperature monitoring and sensors for acoustic signal analysis. Thanks to this setup, it will be possible to keep all the variables influencing the production process under control and ensure prevention of machine breakdown or failure.

VI. CONCLUSIONS

The paper describes the design process of a DT of a production line for hockey balls present in the Smart Factory of OST. The preliminary results show the potential of DT application to increase productivity and reduce energy consumption by assuring the quality of production process. Further activities are needed to complete and fully validate the DT, and to perform the tests required to optimize the production line processes.

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