



**“ENGINEERING, TECHNOLOGY & INNOVATION MANAGEMENT BEYOND 2020:
NEW CHALLENGES, NEW APPROACHES”**



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From Key Business Factors to KPIs within a Reconfigurable and Flexible Cyber-Physical System

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Abstract— In a global market characterized by strong competition and quickly changing boundary conditions, flexible and reconfigurable production systems can rapidly react to both endogenous and exogenous drivers. To this extent, it is necessary to define a new production system model, which can combine the most significant key business factors (KBFs), in order to meet the specified objectives and the relevant KPIs and to control the system. The model can be used within a cyber-physical system, to properly support the different functions and take the right decisions through simulation ICT tools. This research task is part of PERFoRM (Production harmonizEd Reconfiguration of Flexible Robots and Machinery), a European funded project, which aims at developing an innovative manufacturing system based on a new agile concept introducing the implementation of methods, methodologies and strategies for transforming existing production systems into plug-and-produce production ones based on Cyber-Physical Systems technologies. In particular, this paper aims at describing the relationships among the KBFs (Key Business Factors), namely the drivers of the production system, and the relevant KPIs. The model has been validated through an industrial use case, in order to gain important information about constraints and opportunities for improvement in other contexts.

Keywords— KBF; KPI; Cyber-Physical System

I. INTRODUCTION

Smart technologies and the resulting digital transformation lead to improve flexibility and to allow continuous control in industry that helps manufacturing firms to compete in the actual evolving context characterized by unpredictable frequent market changes and the demand for increasingly individualised products with shortened life cycles [1]. The adaptation to this context requires companies to be able to quickly reconfigure their production systems, to follow the rapidly changing markets, allowing higher capacity-flexibility and smaller lot sizes. In this context, it is clear that managerial capabilities, such as proper production management approaches, models and tools should be compatible with rapid reconfigurations of the production system itself, in order to

allow the highest degree of responsiveness and flexibility in adapting to the market changes [1].

In this scenario, the challenge facing businesses is to be able to configure networks to optimize the management of the flow of data and information, the raw materials and the logistics process. It should allow to reorganize the production processes and the structure of the network to operate depending on the type of product to be realized, by adapting to the variability processes of the product itself [2].

Six core characteristics permit such challenge; they are: customization, convertibility, scalability, modularity, integrability, and diagnosability [3]. Convertibility and scalability concern to system capacity and functionality to change its structure, which is enabled by modularity, integrability, and diagnosability. The last characteristic, customization, reduces the traditional trade-off between efficiency and flexibility. In fact, it refers simultaneously to machine and system flexibility and to specific limits and constraints due to particular parts or product family to be realized [4].

Following this characteristics, this paper has the objective to describe a specific model able to provide a responsive new manufacturing approach based on a holistic view of the factory and self-adaptive production capability enabling the ability to rapidly adjust the manufacturing system capacity to market demands and to quickly integrate new functions and process technologies into existing systems [2].

In fact, a new production system model able to provide a reconfigurable aspect to overall production systems is described. In particular, it figures out the relationship between those aspects, variables and external factors that have a potential impact on production process with its Key Performance Indicators (KPIs) used to evaluate and to control its production trend.

Hence, this model is based on the identification of correlation between static factors that can have an influence on industrial plant and its dynamic parameters. The former are considered as those factors that are dependent on the factory business scenario such as, for example market demands, market variability or plant availability etc. and for this reason, they are called as Key Business Factors (KBFs). The latter considers the production parameters used to evaluate the production trend and the process behaviour and for this reason, they are identified as KPIs.

The reconfigurable aspect guaranteed by this model can be analyzed from two different point of view. In fact, establishing this relationship, on one hand, it is possible to understand what KBFs value will be necessary to achieve the desired KPIs and on the other hand, it is possible to evaluate which KPIs would be obtained by choosing specific KBFs a priori.

In particular, to validate its usability in a manufacturing environment, this model has been implemented in an industrial use case. Moreover, operating the industrial use case in a cyber-physical system environment, it was also possible to confirm the adaptability of the model to the new production paradigm that characterize the new era of manufacturing sectors.

II. PRODUCTION SYSTEM MODEL

The final objective of this paper is to provide a specific model to be implemented in a manufacturing production system able to elaborate data coming from production field and to suggest the corrective action to optimize overall production context. For this reason, the first step to be implemented is to define the structure of the model in order to correctly manage the inputs to be inserted and the consequent outputs.

To this end, it has been needed to identify two different levels as depicted in the Fig. 1.

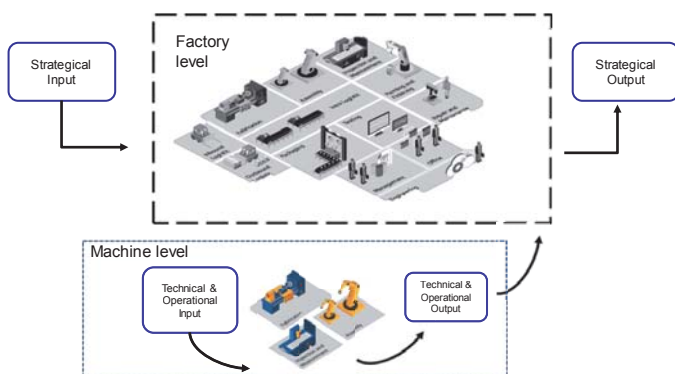


Fig. 1 Production System Model: the structure

The upper level represents overall production plant as it aims at depicting the impact of strategical decision, which can be taken for whole factory. It is called “Factory level” and it requires inputs related the holistic factory and it will provide outputs usable by process owner or whatever user that have

responsibility to overall production plant, such as plant manager or head of department.

The lower level represents the “Machine level” where different equations implemented to describe the mutual relationship among different workstations allow the overall production behaviour description. For this reason, it needs to receive more specific, operational and more technical details. Obviously, the Machine level results lead to obtain the Factory level outputs.

This implies different methodological phases needed to reach the desired results.

They are listed below:

- Factory input definition: overall input that has been decided as a strategical choice by decision maker before to start production process are defined.
- Machine input definition: all data needed to describe the process of single workstation are specified. These data concern to the technical parameters, which characterize the theoretical behaviour and the operational information which describe the effective behaviour of specific workstations when they are involved within the production context.
- Machine output calculation: the process parameters of different machine are collected and they are aggregated in the specific Key Performance Indicators (KPIs). Here the resulting parameters coming from two different inputs layers are elaborated and reformed into outputs.
- Factory Output identification: the results describing the overall Factory behaviour are obtained.
- Overall results Visualization: this phase permits to visualize overall results, highlighting the most strategical. In particular, by containing significant product-specific information about all phases of the production process and by including order-specific information, such as the product price and production costs, the evaluation of each production stage can be generated and visualized with very little effort. Furthermore, using a web-based visualization tool, by KPI monitoring and by performing what-if-analysis based on the variation of several KBFs, support decision-making strategies can be provided.

III. KBF: INPUT DEFINITION

A Key Business Factor can be considered as measures or indicators to best represent the factors that lead to improve customer, operational, and financial performance of particular firms [5]. For this reason, they can be considered as static parameters that have an impact on the performance of production systems. In fact, while KPIs are used to control dynamic factors and monitors the behavior of a selection of single equipment or departments (i.e. dynamic factors) measuring some of their performance in order to put in place local optimization actions, the KBFs are the static parameters that describe the initial condition of production process. For this reason they can be considered as a variables or a driver that, if changed, could imply a different production outputs.

Coherently with the structure of the model, the following tables show KBFs of the model, namely the Factory and Machine Level input, respectively.

In particular, the TABLE I figures out the more strategical decision can be taken before the beginning of the production, clustering them in three groups:

- Production data
- Warehouse data
- Set-up data

TABLE I KBF DEFINITION FOR FACTORY LEVEL

Production data	Definition	Unit of measurement
Working Day	Number of working day during the year	Day (d)
Hour/shift	Hour for each shift	Hour (h)
Shift/ Day	Number of shift for each working day	Number of Shift
Total Demand	Number of pcs requested for each hour	Pcs/hour
Price (€/pcs)	Selling price	Euro (€)
Variable Cost (%)	Variable Cost carried out to product realization	Percentage
Fix Cost (%)	Fix Cost carried out to product realization	Percentage
Margin (%)		Percentage

Set Up Data	Definition	Unit of measurement
Batch size	Number of items that will be produced after a machine has been setup	Pieces for each batch (pcs/batch)

Warehouse data	Definition	Unit of measurement
Dim trolley (m ²)	Trolley Dimension. Trolley are used to stock different items in the warehouse	m ²
Pz/trolley (Nr)	Number of pieces held within each trolley	Pieces for each trolley (pcs/trolley)
Stackability (Nr)	Number of trolley that could be stock for each warehouse line	Number
Interest rate (i%)	Interest rate is the amount of interest due per period, as a proportion of the amount lent, deposited or borrowed	Percentage (%)
WIP Value (%)	WIP value is the percentage value of WIP in comparison with selling price	Percentage (%)
Occupation Cost	The cost for each warehouse squared meter occupied	(€/year/m ²)
Overheads	All costs on the income statement except for direct labor, direct materials, and direct expenses. Overhead expenses include accounting fees, advertising, insurance, interest, legal fees, labor burden, rent, repairs, supplies, taxes, telephone bills, travel expenditures, and utilities.	Percentage (%)

Instead, the TABLE II points out the characteristics needed to describe the initial condition of each workstation. Being the level related to machine behaviour, the Warehouse data has been excluded.

TABLE II KBF DEFINITION FOR MACHINE LEVEL

Production data	Definition	
Cycle Time	Time between the beginning and end of the process of making a product.	Second spent for each Operator/machine involved in the same Working station (s/Op-Mach)
Op-Mach	The number of Operator/machine that are involved in the same working station	Number (Nr)
NC	Non-conforming products	Percentage (%)
Availability	Percentage of production losses due to availability problem	Percentage (%)
Performance	Percentage of production losses due to performance problem	Percentage (%)

Set Up Data		
Set up time	The time required to set up a device for production of a new batch	Second (s/batch)
Op/set up	Operator needed for each set up	Number of operator
Operator Cost	Manpower cost	€/hour/Operator

According to Value stream mapping concept, a visual method using predefined notations and symbols has been selected to assess the value and to determine the workstation process [6]. To this aims, it has been assumed that a table represents each workstation where the different inputs coming from previous levels and the machine outputs are aggregated, such as depicted in Fig. 2.

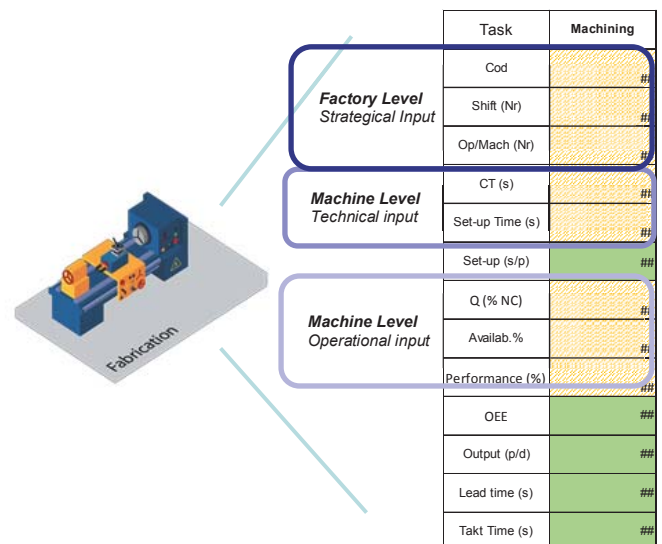


Fig. 2 Workstation representation

As shown in the Fig. 2, the inputs are refigured with yellow dotted line, coherently with different typology of information provided. The other green boxes represent the outputs describing the process values of each workstation. The mathematical equation that correlate the different inputs with these outputs are described in the paragraph below.

IV. MACHINE OUTPUT CALCULATION

As a typical production system can be described as a collection of integrated equipment (i.e. workstations and buffers), it has been needed to elaborate equations able, first of all, to mathematically represent each specific workstation process and then to evaluate the overall Machine level results [7]. For this reason, the output calculation process, starts describing the formulas used to evaluate the green boxes described in Fig. 2.

Following the order of the table, the first evaluable result is the time (s) needed to execute a set-up, allocated for each item composing each batch. For this reason, this value can be obtained with the (1):

$$\text{Set-up (s/p)} = \text{Set up time} / \text{Batch size} \quad (1)$$

The second output concerns to the Overall Equipment Effectiveness (OEE) that can be evaluated with (2), as suggested within the literature ([8]):

Overall Equipment Effectiveness:

$$(1-NC) * \text{Availability} * \text{Performance} \quad (2)$$

In order to make feasible the Throughput evaluation (in the Fig. 2 is called Output), it has been needed to calculate two intermediate equations ((3) and (4)). They are used to evaluate the Actual Daily Machine Availability (s/day) (3) and the Actual processing time (s/p) calculation (4).

The formulas are:

Actual Daily Machine Availability (s/day):

$$\text{Hour/shift} * 60 * 60 * \text{Shift/ Day} * \text{Op/Mach} * \text{Availability} \quad (3)$$

Actual Processing time (s/p):

$$\text{Total Cycle time (for each Working station)} + \text{Set up time} * (1+NC) \quad (4)$$

Knowing values coming from (3) and (4), it is possible to obtain the specific throughput for each workstation, performing the following equation:

$$\text{Output} = \text{throughput (pcs/day)} =$$

$$\text{Actual Daily Machine Availability (s/day)} / \text{Actual Processing time (s/p)} * \text{Performance} \quad (5)$$

Finally, the last two performance indicators able to complete each workstation behaviour, are the Lead Time and Takt time calculation evaluated with these equations:

$$\text{Lead time (s/pcs)} = 1 / \text{Output} * 3600 \quad (6)$$

Takt time (s):

$$\text{Hour/shift} * 60 * 60 * \text{Shift/ Day} * \text{Working Day} / (\text{Total Demand} * \text{Hour/shift} * \text{Working Day}) \quad (7)$$

The (6) leads to assess the Stock level of interoperational buffer of two consecutive workstation. In fact, the Time of Stock can be evaluated with (8):

$$(3600 / \text{Lead time } i - 3600 / \text{Lead time } i+1) * \text{Lead time } i+1 \quad (8)$$

At this point, it is important to understand the relationship among the overall workstations involved in the same process. Therefore, depicting their disposition and certifying their priority that regulate overall production flow, according to [9], it is possible to have a snapshot of overall Machine Level situation at one specific moment, as shown in Fig. 3.

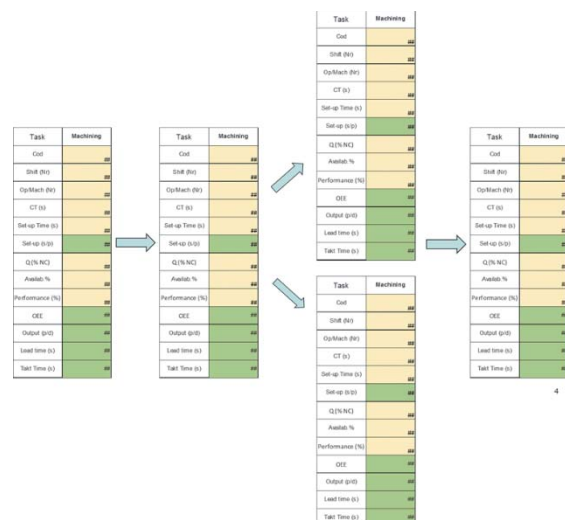


Fig. 3 Machine Level snapshot

Doing this, the following results can be obtained, calculating the following equations:

Bottleneck Machine:

$$\text{Max (lead time) of production line} \quad (9)$$

Output/hour (pcs/h) =

$$3600 / \text{Bottleneck Machine} \quad (10)$$

Lead Time (s):

$$\text{Bottleneck Machine} \quad (11)$$

Theoretical Production time (s) =

$$\sum \text{Total Cycle time (for each Working station)} \quad (12)$$

Total Production Time (s) =

$$\sum \text{Lead time} * \text{Op} - \text{Mach} \quad (13)$$

Total Actual Lead Time (s) =

$$\sum \text{Lead time} * \text{Op} - \text{Mach} + \sum \text{Time of Stock} \quad (14)$$

Stock (pcs) =

$$\text{Batch size} * \text{Item} \quad (15)$$

Stock (hours) =

$$\text{Stock (pcs)} / \text{Output/hour (pcs/h)} \quad (16)$$

V. FACTORY OUTPUT IDENTIFICATION

According to the model structure, being started from Factory and Machine Level Input, through the equation application and through resulting machine output identification, it is possible to assess the Factory Level output as described in Fig.4.

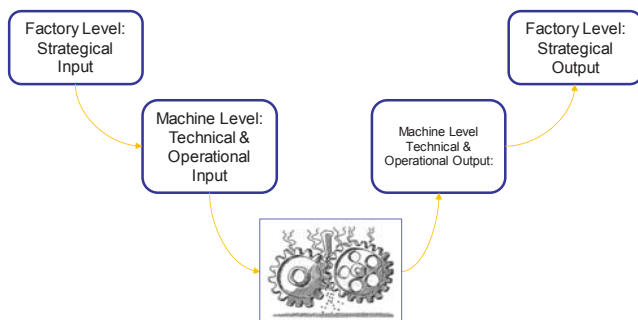


Fig. 4 Model application process

As far as these results are concerned, a specific focus on the cost analysis influenced by initial condition (KBFs) has been carried out. In particular, they are split in three different classes

- Production Losses Cost
- Set up cost
- Warehouse cost

The first one takes into account the KBFs and KPIs collected from different levels and shown in the TABLE III .

TABLE III PRODUCTION LOSSES' DATA

Set up time (s/batch)	Factory Level KBFs
Batch size (pcs/batch)	Factory Level KBFs
Total Demand (p/h)	Factory Level KBFs
Shift/day	Factory Level KBFs
Hour/shift (h)	Factory Level KBFs
Working days (d)	Factory Level KBFs
Price (€/pcs)	Factory Level KBFs
Variable Cost	Factory Level KBFs
Fix Cost	Factory Level KBFs
Margin	Factory Level KBFs
Lead Time (s)	Machine level KPIs

From these data, the evaluation of Production Loss (pcs) can be assessed through the equation (17):

Production Loss (pcs) =

$$\text{Set up time (s/batch)} / \text{Batch size (pcs/batch)} * \text{Total Demand (p/h)} * \text{Shift/day} * \text{Hour/shift} * \text{Working days (d)} / \text{Lead time (s)}$$

(17) leads to assess the overall Cost of Production Loss (€), as it can be evaluated using the following formulas:

Cost of Production Loss (€) =

$$\text{Production Loss (pcs)} * \text{Price (€/pcs)} * (\text{Fix Cost} + \text{Margin}) \quad (18)$$

The TABLE IV presents the list of the KBFs and KPIs collected needed to the evaluation of the total Set-up number realized to meet market demand and the resulting time required to apply these set-ups.

TABLE IV SET UP DATA

Op/set-up	Factory Level KBFs
Operator Cost (€/Op/h)	Factory Level KBFs
Set up time (s/batch)	Factory Level KBFs
Batch size (pcs/batch)	Factory Level KBFs
Total Demand (p/h)	Factory Level KBFs
Shift/day	Factory Level KBFs
Hour/shift (h)	Factory Level KBFs
Working days (d)	Factory Level KBFs

The equation used to assess these values are described below:

Set-up (number) =

$$\frac{\text{Total Demand (p/h)} * \text{Shift/day} * \text{Hour/shift (h)} * \text{Working days (d)}}{\text{Batch size (pcs/batch)}} \quad (19)$$

Total Set-up time (h) =

$$\text{Set-up number} * \text{Set up time (s/batch)} \quad (20)$$

At this point, it is possible to calculate the overall Set-up Cost using equation (21):

Set-up Cost (€) =

$$\text{Total Set-up time (h)} * \text{Op/set-up} * \text{Operator Cost (€/Op/h)} \quad (21)$$

The warehouse cost can be calculated from the data inserted in the TABLE V.

TABLE V WAREHOUSE DATA

Price (€/pcs)	<i>Factory Level KBFs</i>
Stock (pcs)	<i>Factory Level KBFs</i>
Dim trolley (m ²)	<i>Factory Level KBFs</i>
Pz/trolley	<i>Factory Level KBFs</i>
Stackability	<i>Factory Level KBFs</i>
Interest rate (i%)	<i>Factory Level KBFs</i>
WIP Value (%)	<i>Factory Level KBFs</i>
Occupation Cost (€/year/m ²)	<i>Factory Level KBFs</i>
Overheads (%)	<i>Factory Level KBFs</i>
Overheads Cost (€)	<i>Factory Level KBFs</i>

TABLE V provides data needed to know the area occupied by items stocked and the resulting cost.

The former value is obtained with this formula:

$$\text{Occupation Area (m}^2\text{)} =$$

$$\frac{\text{Stock (pcs)}}{\text{Pz/trolley} / \text{Stackability}} * \text{Dim trolley (m}^2\text{)} \quad (22)$$

Instead, the latter considers the Working Progress (WIP) Cost influenced by interest rate (i %) and item price, according to equation (23) :

WIP Cost (€) =

$$\text{Stock (pcs)} * \text{Price (€/pcs)} * \text{interest rate (\%)} * \text{WIP value (\%)} \quad (23)$$

Adding the results of (22) and (23), the overall Warehouse Cost can be evaluated.

VI. OVERALL RESULTS VISUALIZATION

The visualization phase is executed with specific User Interface (UI). It was designed to allow the decision maker user to, in a responsive manner, be aware of the key relevant parameters present at Machine Level. The tool constantly collects the necessary data generated at shop-floor and continuously updates the KPIs to be monitored (as defined in section IV).

From Fig. 5, it is possible to observe that the UI has some relevant features, showing namely two abstraction levels to the decision maker. First, from Fig. 5 (left), the decision maker is presented with an aggregated perspective, where, for each of the KPIs, it is shown:

- **Target:** desired value to be reached, as needed to fulfill the production plan;
- **Actual:** latest KPI calculation, achieved based on the collected data;
- **Cp:** is the process capability ratio (PCR) [10];
- **Cpk:** is a modified Cp where the process centering is taken into consideration [10];

With this information, the decision maker has a quick glimpse of the current, and overall, status.

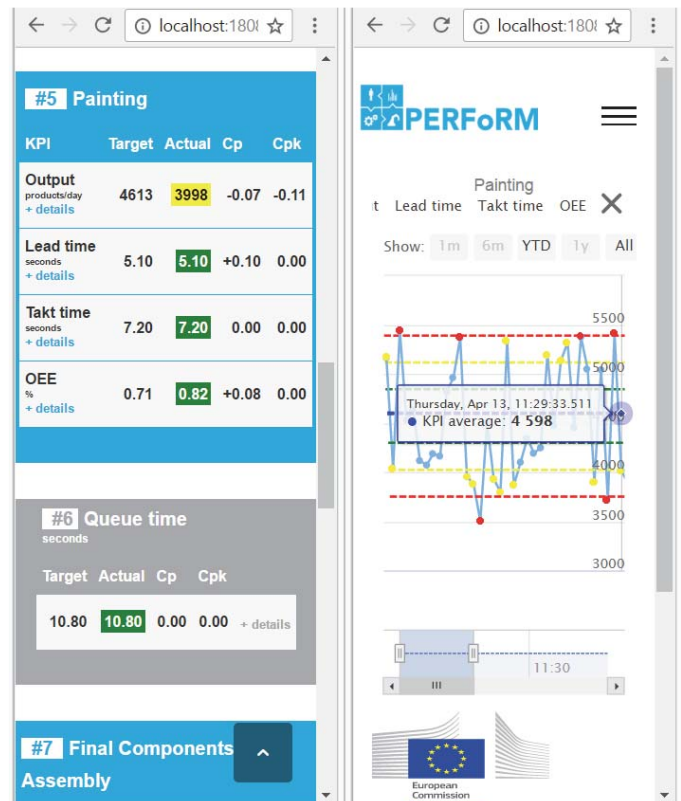


Fig. 5- Dynamic KPI monitoring tool UI

The UI presents the information following the production stations layout in a sorted order. Colors are also used for a visually enriched experience, enabling the user to quickly detect problematic situation.

A detailed view of each KPI is also shown by opening a new UI perspective, displaying its evolution over time (see Fig. 5 (right)). The plotted graph is annotated with relevant information, namely 3 pairs of two limits on control charts at $\pm 1\sigma$, $\pm 2\sigma$ and $\pm 3\sigma$ and a line depicting the overall points average value. Additionally, the data values are annotated with a visual color denoting problematic situations that might had occur.

The applied rules follow the guidelines provided by the Western Electric Rules [11], particularly marking points when, “one data point falls outside the $\pm 3\sigma$ ”, “two out of three consecutive data points fall beyond the $\pm 2\sigma$ warning limits”, “four out of five consecutive data points fall beyond the $\pm 1\sigma$ limit, on the same side of the centerline” or “eight consecutive data points fall on one side of the center line.

Globally, the user has a feature-rich, multi-device UI that, from anywhere, allows the identification of the current status of shop-floor results.

Finally, Fig. 6 shows the what-if analysis application. On the bottom the different KBF values while on the top the KPIs describing both overall system performance (collected from (9) to (16)) and specific workstation behaviour (collected (1) to (9)) are figured out.



Fig. 6 Output visualization of both Factory level and Machine level

VII. THE INDUSTRIAL USE CASE

The industrial use case has been implemented within the EU-project PERFORM and it concerns to home appliance production [12].

The production process is composed of a production line made by different machines and buffers and it is represented in Fig. 7. In particular, the line ends with decoupling buffer that aims

at provide different semi-finished products to four parallel lines.

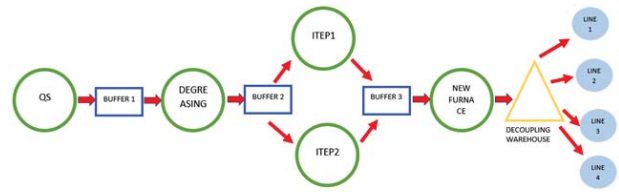


Fig. 7 Use Case: production line

As these lines are identical in terms of process and in terms of market demand to be satisfied, it has been decided to model a unique total demands impacting directly on the decoupling buffer. For this reason, the overall Machine Level of this industrial use case has been modeled as shown in the Fig. 8.

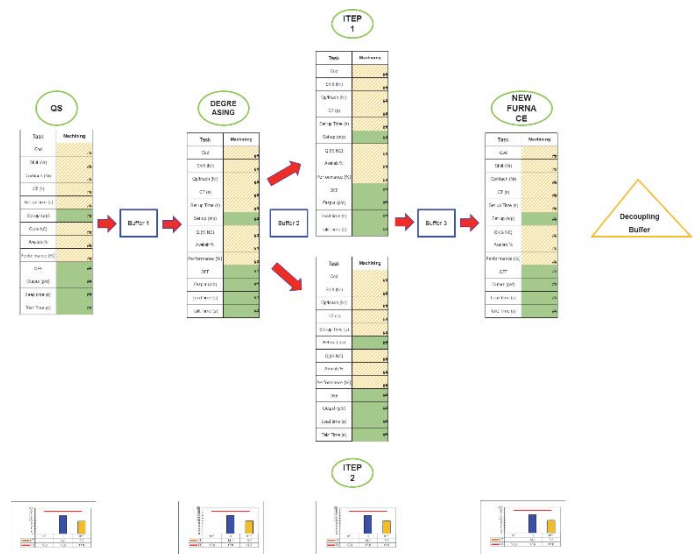


Fig. 8 Use Case: Machine Level model

Applying the formulas described before, different KPIs has been aggregated into strategical information. In fact, in addition to providing specific results (Fig. 6 on the right) with aforementioned equations, it also illustrates the relationship with consecutive machines in terms of Throughput, Lead-time and Takt Time. In particular, considering the Takt Time (TT) as the maximum threshold for product realization (red line in Fig. 9) and knowing the specific Lead-time of upstream and downstream workstation, it is possible to manage the different KBFs in order to maximize the production process balance and the workstation utilization rate. Furthermore, the analysis represented in

Fig. 9, identifies the bottleneck that determines the overall production pace, suggesting which is the workstation needs to be instantaneously improved.

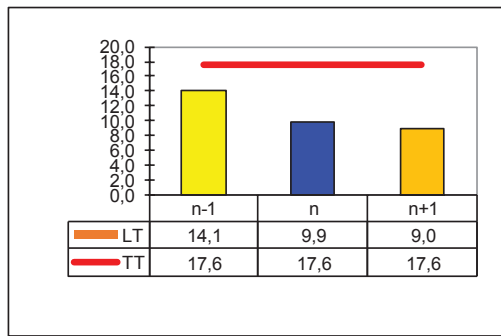


Fig. 9 Workstation Results

The second result is depicted in Fig. 10 where the three costs are compared. The figure points out that the Cost of Production Loss (blue line) has the highest impact on the overall cost (yellow line). In particular, Warehouse Costs (orange line) have to be considered according to the right scale (which scores from 0 to 70000€). On the other hand, the other considered costs refer to the left scale (which scores from 150000€ to 2100000€). From these evidences, it can be state that the most convenient strategy for this use case is to maintain a big amount of items within decoupling buffer rather than to continuously adjust the batch size needed to meet market demand.

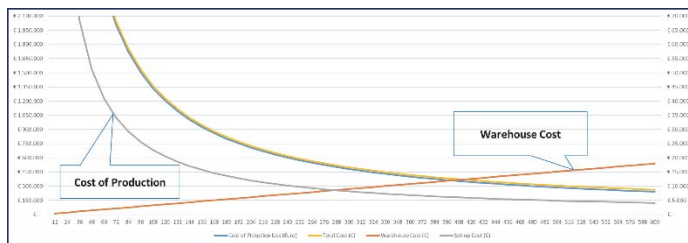


Fig. 10 Overall Cost representation

VIII. APPLICATION ON CYBER-PHYSICAL SYSTEM

As described by J.Lee [13],[14] the Cyber Physical Systems provides different levels of functionality allowing to adapt automated production equipment and systems rapidly, reliably, safely, and cost-effectively in order to meet changing needs and requirements and to obtain, seamlessly integrate, and optimally use [15]. These functionalities are guaranteed, as described in [15], by the integration of three different capabilities:

- measurement and sensing capability enabling to capture what information can be sensed to measure the state of the factory);
- modeling and simulation enabling how well this information is used to model and simulate factory activities;
- optimization and control enabling how best to use it to continually optimize manufacturing production:

In this context, the model described before can be fully involved. In fact, by providing the relationship between static and dynamic parameters, it can be exploited to replicate the factory performance, to conduct static simulations and to apply the sensitivity analysis needed to support the decision process.

Therefore, the ability to detect a relationship between the KBFs and KPIs allows to create a predictive model able to foresee how production process takes place given economic context, but also to strategically manage the process variables and thus to control its operations. For these reason, it can be developed through ICT tools and be applied within cyber-physical system to properly support the different functions and take the right decisions.

IX. CONCLUSION

This paper has proposed a specific production system model able to point out a straightly relationship between KBFs and KPIs. Principally, this connection can lead to obtain two benefits. The former is the optimization of Machine Level. In fact, knowing the KBFs already selected, the model produces a static snapshot of the situation in the system at a specific time, highlighting the eventual problem of saturation, utilization rate and bottleneck as a potential element to be solved in order to have a full production improvement. It is also allowed by UI that collecting raw data and calculating relevant KPIs helps the assessment, in a responsive manner, of the current status of the shop-floor.

The latter is based on simulation activity aiming at evaluating the system performance. In this case, a what if analysis can be applied. In fact, changing different KBFs, multiple scenarios can be evaluated aiming at choosing the best combination of KBFs able to guarantee the most advantageous performances. Therefore, it provide decision support systems based method, exploitable by different levels of decision maker: from process owner, through plant manager or logistic manager towards head of department or foreman.

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