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Abstract: In the traditional software development cycle, requirements gathering is considered the most critical phase. Getting the requirements right early has become a dogma in software engineering because the correction of erroneous or incomplete requirements in later software development phases becomes overly expensive. For product-service systems (PSS), this dogma and standard requirements engineering (RE) approaches are not appropriate because classical RE is considered concluded once a product service is delivered. This paper proposes a novel framework that enables the customer and the product engineer to co-design smart products by integrating three novel and advanced technologies to support: view-based modelling, visualization and monitoring, i.e., Product-Oriented Configuration Language (PoCL), gamification and Complex Event Processing (CEP), respectively. These create a "*digital-twin*" model of the connected 'smart' factory of the future. The framework is formally founded on the novel concept of manufacturing blueprints, which are formalized knowledge-intensive structures that provide the basis for actionable PSS and production "intelligence" and a move toward more fact-based manufacturing decisions. Implementation and validation of the proposed framework through real-life case studies are ongoing to validate the applicability, utility and efficacy of the proposed solutions.

1 INTRODUCTION

Industry 4.0 is progressively transitioning conventional factories to smart components and smart machines to enable an ecosystem of connected digital factories. A key enabler of Industry 4.0 is the "*digital-twin*" model of the connected 'smart' factory of the future, where computer-driven systems create a virtual copy of the physical world and help make decentralized decisions with much higher degree of accuracy (Grieves, 2014).

The digital-twin approach enables manufacturers to overlay the virtual, digital product on top of any physical product at any stage of production on the factory floor, and analyze its behavior so that product designers and engineers can make informed choices about materials and processes using visualization tools, e.g., 3D CAD/CAM tools, during the design stages of a digital product and immediately see the impact on a physical version of the product. The ability to combine the digital-twin approach with support for smart products, improved processes and empowerment of human operators is the key to unlocking the real underlying value of Industry 4.0.

A few recent studies (Sierla et al., 2018; Schluse et al., 2018; Lu and Xu, 2018; Ameri and Sabbagh, 2016; Nee et al., 2012; Berg and Vance, 2017) have applied the digital-twin approach and visualization tools to support product design, production process monitoring and control, and product services, such as maintenance. However, these studies still suffer from severe drawbacks. First, they do not provide an integrated and comprehensive digital-twin approach to support the complete smart product lifecycle from the stages of requirements elicitation, product design, customization, and production monitoring. Second, they lack the integration of product, service and production-related knowledge with advanced visualization support. Finally, these approaches lack intuitive user-friendly interfaces that expedite a

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particular activity (e.g., product customization), and do not use emergent advanced techniques such as gamification for improving the user engagement in different activity.

To address the aforementioned limitations in the existing works, the research presented in this paper realizes the digital-twin approach to support the key phases in the lifecycle of a smart PSS (product-service system). In our earlier work (Papazoglou and Elgammal, 2018), we have introduced the PSS lifecycle. It provides a closed monitoring feedback loop that enables continuous product and service improvements based on the novel concept of manufacturing blueprints, which formally captures product-service and production-related knowledge (Papazoglou and Elgammal, 2017; Papazoglou and Elgammal, 2015). Blueprints integrate dispersed manufacturing data from diverse sources and locations, which includes and combines business transactional data and manufacturing operational data to gain full visibility and control, and provides the basis for production actionable "intelligence".

The proposed framework considers smart product ideation and customization, as well as monitoring of its actual production. The framework consists of an integrated product designer component and a monitoring Dashboard, which enables the customer, in collaboration with the product designer/engineer, to co-design customized PSS via a unique gamification experience. The user-friendly 3D product designer component offers a fancy gaming experience during the product design and customization process. To enable on demand PSS customization and a customer-centric approach, the PSS lifecycle supports complementary stakeholders' perspectives by making use of a novel Product-oriented Configuration Language (PoCL) (Elgammal et al., 2017). Utilizing PoCL in conjunction with gamification, customers, in collaboration with product designers, can specify the desired product and service characteristics. The monitoring Dashboard displays the products, machines, sensors and other artefacts in a dedicated interactive interface, and is able to provide a 3D representation of the graphical objects. The Dashboard also serves as a mediator between the shift in-charge or control room manager / operator, who supervises and monitors the manufacturing process, and the factory-floor environment. The monitoring framework utilizes CEP technology (Etzion and Niblett, 2010), which is event-based processing that combines data from multiple sources, to infer events or patterns that suggest more complicated circumstances. Implementation and validation of the proposed framework through a real-world case study (taken from the H2020 ICP4Life EU Project) is performed to validate the applicability, usability and efficacy of the proposed solutions.

The remainder of the paper is structured as follows: Section 2 discusses related efforts in the areas of digital-twin and visualization approaches for production co-design and production process monitoring. Section 3 presents the proposed PSS co-design framework via PoCL, gamification and CEP. This is followed by presenting the current implement-tation efforts in Section 4 Finally, Section 5 concludes the paper and highlights future work directions.

2 RELATED WORK

We consider related studies from the two key research issues in this paper, that is, digital-twin, and visualization platforms for product co-design and shop floor monitoring.

2.1 Digital-Twin

Tao et al. (2018) proposed a framework that utilizes the raw data from the physical product and its digital-twin to support product design, production, and services, such as maintenance. Sierla et al. presented the concept of digital-twin centric control, where the digital twin derived from a product model creates assembly plans, and orchestrates the resources in a production cell. Schluse et al. (2018) introduced the concept of experimentable digital-twins, which are model-based simulations of digital-twins. The studies in (Lu and Xu, 2018; Ameri and Sabbagh, 2016) use ontologies to represent the resources in a factory-floor to create their digital-twins.

As opposed to these works that mostly consider only limited aspects of the Product Lifecycle Management (PLM), the approach presented in this paper is built on top of the manufacturing blueprints approach (Papazoglou and Elgammal, 2017; Papazoglou and Elgammal, 2015) that enables an integrated and comprehensive digital-twin approach to support the complete smart product lifecycle from the stages of requirements elicitation by means of the Product-oriented Configuration Language (PoCL), to product design, customization, and production planning.

2.2 Visualization Platforms for Product Co-Design

According to the recent reviews of the related literature (Nee et al., 2012; Berg and Vance, 2017), the advanced visualization technologies, such as virtual/augmented reality and 3D CAD/CAM, have been used in collaborative manufacturing environments to support such activities as product inception, co-design, production planning, and maintenance. However, overall, they have several key limitations. First, they lack the integration of product-service and production-related knowledge with their visual supports. Such knowledge can enable consistency checking of visual models, and support informed decision making during a particular user activity (e.g., product design and customization) (Rocca, 2012; Chandrasegaran et al., 2013). Second, these approaches lack intuitive user-friendly interfaces that expedite a particular activity (e.g., a user interface tailored to product customization). They also do not apply the techniques for improving the user engagement in the activity, such as gamification. Several recent works have concluded that gamification in manufacturing environments can improve the quality of the work and the performance of the users/workers (Korn and Schmidt, 2015).

To overcome the above key limitations in the current literature, the visualization platform presented in this paper utilizes the blueprinting approach that readily supports production-related activities ranging from the conception and configuration of a customized product all the way to planning and digital production, by gathering, storing and processing "smart actionable data" from every point of the product lifecycle. Moreover, the user-friendly PoCL helps customers to collaboratively and visually create, validate and optimize manufacturing design plans with product designers/engineers, augmented by gamified 3D CAD/CAM interactive capabilities.

2.3 Visualization Platforms for Shop Floor Monitoring

A few studies have used complex event processing (CEP) for monitoring and control of production processes in the factory-floor (Grauer et al., 2011; Babiceanu and Seker, 2016; Estruch and Heredia, 2012; Izaguirre, Lobov and Lastra, 2011). Grauer et al. (2011) used CEP to perform real-time monitoring and control of processes in manufacturing enterprises. The data is collected from different automation systems in real-time. The CEP engine detects complex events (e.g. alarms) from this raw data, and the dedicated tools visualize the detected complex events. Estruch and Álvaro proposed a generic architecture for event-driven manufacturing process management (EDMPM). It consists of three main layers: connectivity layer (to enable communication with existing information systems in the enterprise), process execution layer (to enact event-driven manufacturing processes) and a user interface layer (to support customizable KPIs visualization and analysis). Izaguirre et al. used CEP to support the interoperability of the events generated using two different standards for device communication protocols by the devices at the factory-floor.

In comparison with the above works, this paper proposes a platform that applies CEP to derive the meaningful production process events (e.g., anomaly-detected event) from the raw sensor data at the factory-floor, and visualize such events in an interactive Dashboard. Moreover, we use the integrated and formalized knowledge (i.e., manufacturing blueprints) related to product-service, and production to drive the production monitoring.

3 SMART PRODUCT CO-DESIGN AND MONITORING FRAMEWORK

The proposed framework is shown schematically in Figure 1. It is firstly concerned with smart product ideation and customization (upper left hand-side of figure). This is achieved through the integration of a set of interplaying advanced technologies including the novel PoCL that we have previously introduced in our previous work (reference omitted for blind review) and gamification. The framework also supports monitoring of actual requested customized product production based on CEP and provides an interactive graphical Dashboard (lower part of Figure 1). More specifically, a user-friendly graphical gamification tool, which is based on PoCL, is proposed that allows a user to define in collaboration with the product designer customized smart product requirements. In the next sub-sections, the smart product ideation and customization based on PoCL and gamification is first discussed, followed by its integrated monitoring approach.

3.1 Smart Product Ideation and Customization

PoCL is a model-based user-friendly Domain-Specific Language (DSL) that helps customers to collaboratively create, validate and optimize manufacturing design plans concurrently with product/service designers during the stages of the requirement elicitation process. PoCL is a view-based modelling language that supports different stakeholders by tailor-made interfaces at varying

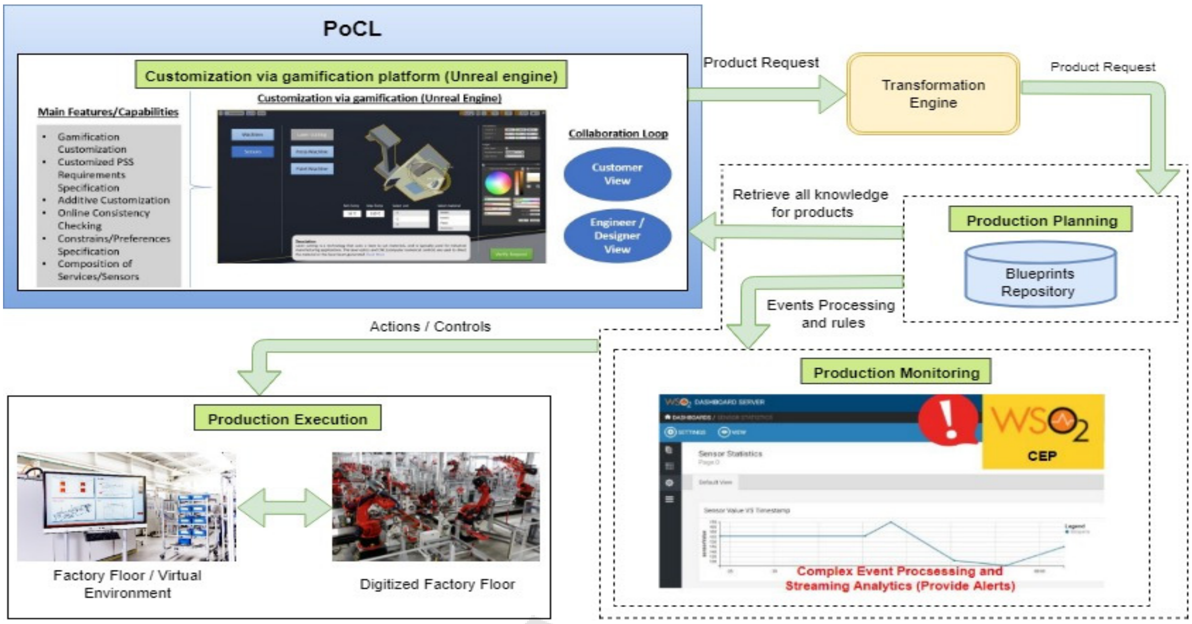


Figure 1: Proposed Smart product co-design and monitoring framework.

levels of abstraction that support the associated user profile. In essence, PoCL allows customers to imagine and gradually create a virtual product, amplifying their ideas and clearing the way to better design and innovation.

PoCL supports the following: (i) Digital product features framing, which focuses on collation of product ideas that can inspire new and innovative products by supporting unique extensions and adaptations of base products to create customizable ones; (ii) Progressive product configuration sketching and framing, which defines the requirements of the products, produces prototypes by managing product parameters and evaluates the cost implications of potential design improvements.

PoCL and its gaming counterparts are formally founded on the novel concept of the widely tested and validated manufacturing blueprints (blueprints for short, which we have previously introduced in (references omitted for blind review). Manufacturing blueprints semantically capture product-service and production-related knowledge. Manufacturing blueprints rely on model-based design techniques to manage and inter-link product data and information (both its content and context), product portfolios and product families, manufacturing assets (personnel, plant machinery and facilities, production line equipment), and, in general, help meet the requirements (functional, performance, quality, cost, time, etc.) of an entire manufacturing network. This information can be collated and put within a broader operational context, providing the basis for manufacturing actionable "intelligence" and a move toward more fact-based decisions.

The information in the Blueprints describes, through ontological forms, the setting of the machinery at the factory-floor, machines' capabilities, their sensors and actuators. Blueprints also offer a way to define certain properties for a customized product. The latter is used to query and match the description of the desired product with existing Blueprints in the repository so as to retrieve Blueprint product instances stored that are very close to, or relevant with the desired customization (represented by the input arrow named "Retrieve all knowledge for products" in Figure 1). This could include, for example, components and their composition, relationships between components, materials, services (including sensors and their relationships), etc.

The outcome of the "Customization via gamification" component is a new "Customer Smart Product Request" in the format of the adopted gamification technology/engine. The smart product request is then transformed into Blueprints representation (an OWL representation; details are found in (references omitted for blind review) using a "transformation engine", which is eventually stored in the Blueprints Repository.

The integration of the Manufacturing Blueprint Data Model with PoCL embodies production-domain knowledge along with the rules of what type of knowledge must be recorded about each manufacturing element, how these elements can be connected and how this knowledge can be aggregated, conserved and reused.

3.2 Smart Product Monitoring

The proposed Dashboard serves as a mediator between the shift in-charge or control room manager/operator, who supervises and monitors the whole manufacturing process, and the factory-floor environment. In this context, this person is able to define for each machine, and each sensor installed in a machine, the type of values it collects, their timing (frequency) and, most importantly, some monitoring rules and actions based on threshold values (minimum, or maximum, or both), which are set to denote ranges of normal operation. The sensors continuously gather information (e.g. temperature, pressure, humidity etc.) which is then compared in real-time against the normal operation thresholds. In case a deviation is observed from 'normality', an alerting process is initially triggered which produces certain types of alerts to notify the person in charge that one or more anomalies are detected at the factory-floor.

This monitoring process, as shown right bottom hand-side of Figure 1, is enabled by utilizing and integrating CEP technology. Thus, this process takes advantage of CEP's event processing capabilities to combine data from multiple sources and infer events or patterns that suggest more complicated circumstances. The detection of a violation of any of the defined monitoring rules (and/or thresholds), that are stored and maintained in the Blueprints repository may trigger an alerting process, as well as the (semi) automatic execution of appropriate response action(s) defined for the same type of violation.

This could be in the simplest case confined to sending an alarm signal to the operator (displayed on the Dashboard), and in a more automated/sophisticated manner, extended to sending signals/actions/controls to the factory-floor that drive the actuators on the machines. For example, a possible action as a response to the detection of a rise in temperature for a welding machine (as compared to the defined threshold), is to send a signal to the actuators at the factory-floor to turn-on specific ventilation or air-conditioning machinery to cool the place and lower the temperature.

This work currently implements the definition of the threshold values and the actions to be taken when emergency cases arise, and assumes that the execution of these actions is handled by another (existing) module, the latter being the subject of another research work by the authors.

4 IMPLEMENTATION

This section presents a demonstration example where the framework/approach described in section 3 is applied on a real-world use case. The customization-gamification process is developed in the Unreal Engine environment (https://www.unrealengine.com) Realizing PoCL with gamification offers a fancy gaming experience during the product customization process, which significantly improves the quality of experience of the involved stakeholders. The graphical Dashboard (as shown in

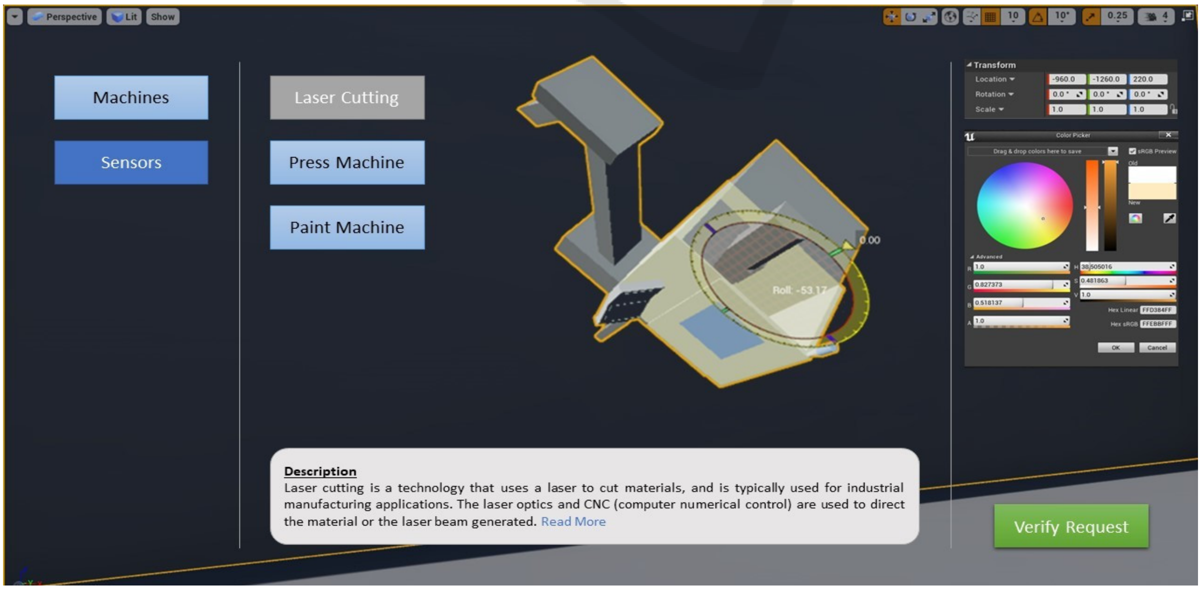


Figure 2: Dashboard functionality allowing gamified customization in Unreal Engine.

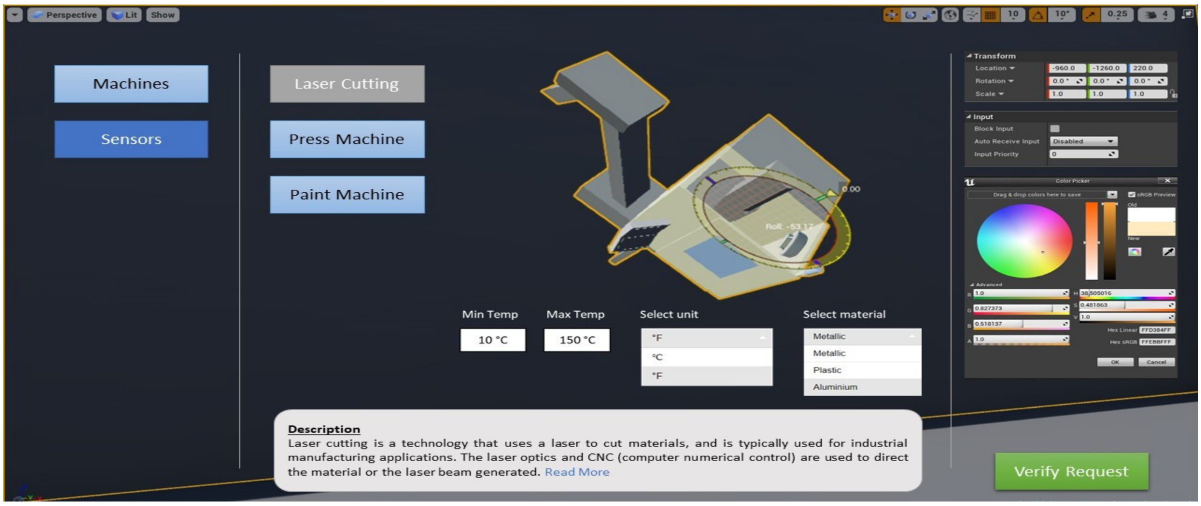


Figure 3: Customer's Dashboard for sensor and connection to the machine.

figure 2) displays the products, machines, sensors and other artefacts in a dedicated interactive interface, and it is able to provide a 3D representation of the graphical objects.

The Dashboard offers a set of simple and ergonomic graphical actions with which a potential customer finalizes the details of customization when ordering a new product.

Firstly, as presented in Figure 2, in order to add a new machine in the system (the product to be ordered and developed in this case is a machine) a user (customer) must first select the "Machines" from the list of the main categories (left sub-figure) and then define its type (right sub-figure). For the purposes of our demonstration we have set-up three types of machines, a CO2 Laser, a Laser Cutter and a Drilling Machine. Once a machine is added into the system the user is able to view it in 3D, set its properties, rotate it, change its skeleton, change its colour etc.

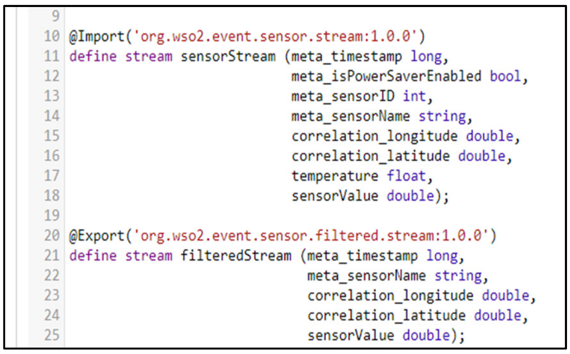
In the next step shown in figure 3, a user wishes to add certain sensors on a specific machine. In order to do so (s)he must first select the operation "Sensors" from a list of main functional categories (left sub-figure) and then specify the type of sensor, its thresholds and the machine the specific sensor operates on (right sub-figure). In our example four types of sensors with certain properties were defined: a "Temperature" sensor, with a minimum value of 30°C and a maximum value of 100°C, a "Humidity" sensor with minimum value of 40%RH and a maximum value of 80%RH, a "Motion" sensor with minimum distance of 1m and maximum distance of 15m (denoting the range of distance covered to detect motions) and a "Light" sensor with start-time set to 21:00pm and end-time to 07:00am (this is the time frame for the light sensor to perform its action: when the Motion sensor detects a movement and the time recorded is within the range of the Light sensor then a light goes-on; as long as no movement is detected, the light sensor remains inactive).


```xml
<?xml version="1.0" encoding="utf-8"?>
<factory>
<rproduct family="machines">
    <name>Laser Cutting</name>
    <rnparts>4</rnparts>
    <rsizex>100</rsizex>
    <rsizey>200</rsizey>
    <rsizez>100</rsizez>
    <rcolor>silver</rcolor>
</rproduct>
</factory>
```

```xml
<?xml version="1.0" encoding="utf-8"?>
<factory>
  <sproduct category="sensors">
    <family>sensors</family>
    <type>temperature</type>
    <sensorName>SensorTemp</sensorName>
    <unit>celsius</unit>
    <material>aluminium</material>
    <maxTemp>250</maxTemp>
    <minTemp>50</minThresTemp>
  </sproduct>
</factory>
```


Figure 4: An example in xml of the product request generated by the Unreal Engine.

Figure 4 outlines the data extracted from the Unreal Engine according to the demonstration example. First, the data is translated into an OWL representation and then using PoCL it is converted into Blueprints. As mentioned in the Methodology section, users have the ability to process the sensor



```
@Import('org.wso2.event.sensor.stream:1.0.0')
define stream sensorStream (meta_timestamp long,
                            meta_isPowerSaverEnabled bool,
                            meta_sensorID int,
                            meta_sensorName string,
                            correlation_longitude double,
                            correlation_latitude double,
                            temperature float,
                            sensorValue double);

@Export('org.wso2.event.sensor.filtered.stream:1.0.0')
define stream filteredStream (meta_timestamp long,
                              meta_sensorName string,
                              correlation_longitude double,
                              correlation_latitude double,
                              sensorValue double);
```

Figure 5: Creating an execution plan by using a query.

fields defined in the previous steps and create execution plans based either on certain queries, as presented in figure 5, or by creating their own scenario without having to write a query, as shown in figure 6.

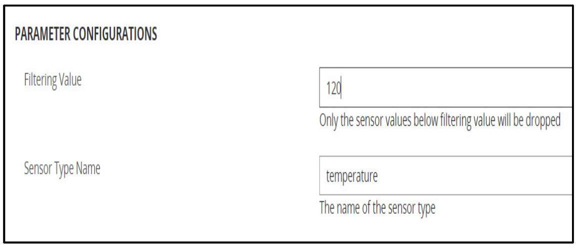


Figure 6: Alterative way for creating a scenario.

Figure 6 presents the alterative, easier way for creating a scenario in which the user defines sensors and threshold values through dedicated GUI forms. Once the scenario is created, the associated graph appears as a result of that scenario, as shown in figure 7; the graph displays temperature sensor values above 100°C.

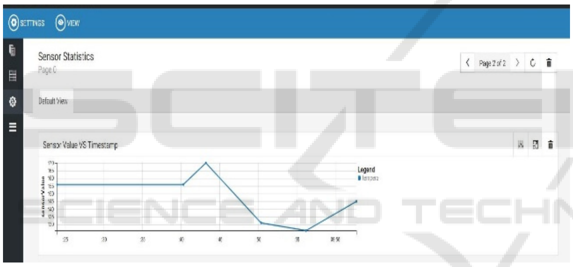


Figure 7: A scenario which displays all temperature sensor values that are greater than 100°C.

Statistical information is also displayed on the Dashboard screen as depicted in figure 8.

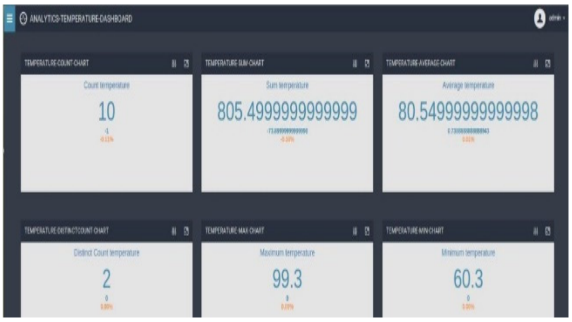


Figure 8: Statistics Dashboard about real-time values from temperature sensor.

Figure 9: Notification alert for temperature value greater than 200°C and action confirmation.

Finally, the case of a notification alert popping-up on the Dashboard screen and requiring the shift manager to confirm the action related to this alert is presented in figure 9.

5 CONCLUSIONS AND FUTURE WORK

The present paper introduced a new framework that facilitates smart product ideation and customization, and provides the means for monitoring the production process. The framework offers the ability to a customer to co-design customized PSS via a unique gamification experience and also integrates with a Product-oriented Configuration Language to specify product and service characteristics. A dedicated interactive monitoring Dashboard displays products, machines, sensors and other artefacts using a 3D graphical representation. The Dashboard essentially connects the control room manager/operator with the factory-floor environment and assists in the supervision and control of the manufacturing process utilizing CEP technology. The latter supports event-based processing by combining data from the various sources at the factory-floor. The proposed framework is being demonstrated and validated using a real-world case study in terms of applicability, usability and efficiency.

Future work will concentrate on: (i) (semi-) automating recovery actions by seeding self-adaptiveness and self-healing capabilities into the monitoring component of the framework, moving towards the vision of self-autonomous smart factory, and (iii) augmenting the Dashboards with sophisticated visualization features by supporting augmented and virtual reality, and (iii) designing and developing advanced querying and recommendations/matching capabilities, which will assist the re-usability of previous customization efforts during the smart product ideation phase.

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