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Towards intelligent and sustainable production: combining and integrating online predictive maintenance and continuous quality control

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Abstract

The paper addresses intelligent and sustainable production in the sense of combining and integrating online predictive maintenance and continuous quality control. The rationale for combining and integrating them is that continuous quality control can provide input to the online predictive maintenance in cases where no signs of maintenance issues have been indicated and inadequate output is produced (and the process parameters cannot be adjusted in order to meet the output specifications). The paper outlines the first part of an action research effort at Gestamp HardTech AB in Sweden, whose objective is to keep its position as a world-leading provider of press-hardened vehicle parts. The first initial design criteria concerned with simplicity and low-cost was changed after learning more details and what can be accomplished, and the updated first design criteria focused instead on robustness, high-quality output and future-proofing. The intermediary result is an action plan for the technical change, whereas the organizational change will be addressed later during the action research effort.

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Keywords: continuous quality control; intelligent; online predictive maintenance; production; sustainable.

1. Introduction

The paper concerns the first phase and part of the second phase, i.e., diagnosing and planning action, of an action research effort at a manufacturing company, Gestamp HardTech AB, which produces advanced and complex press-hardened components for the vehicle industry.

In order to increase competiveness and economic as well as environmental sustainability, new and innovative ways need to be tried and implemented when successfully verified. However, all such ways do not need to be disruptive but can involve combination and integration of existing concepts that together will create more value than when used separately. This paper concerns two such concepts: online predictive maintenance of production equipment and continuous quality control of production process parameters as well as the output from the production process. **Online predictive maintenance** entails, in this paper, using sensors and other means to online monitor and collect data pertaining to an asset and its operational activities, output and condition. This does not mean that all collected data are stored; thus, data that are to be used and stored must be actively selected. The data, or rather various parameters, must be modeled in order to find thresholds and relations in between parameters that can be used to indicate potential problems arising (i.e., diagnostics) and maintenance need (i.e., prognostics). Thus, modeling and the analytics, as well as the ability to quickly traverse and mine large amounts of various data, are key. During the analytics, data from other complementary sources such as meta-data, vendor databases or historic data, etc., can be combined and mined together with the data passing by online as well as recent data stored. Subsequently, analytic results derived (e.g., prognostics and asset degradations) need to be presented and visualized adequately in order to support decision-making processes. In addition, in case the analytics reveal signs of immediate failure within the asset monitored, notifications/warnings for reactive maintenance, as well as emergency shutdowns or graceful degradation schemes, can be issued. **Continuous quality control** encompasses, in this paper, online monitoring and collection of production process

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parameters as well as measurements of the output from the production process. As in the online predictive maintenance described above, the data or parameters need to be modeled in order to find which ranges, thresholds and relations in between parameters can lead to diagnosis and reveal arising or actual quality problems – which will render output that does not meet the specifications.

The rationale for **combining and integrating** these are that if the online predictive maintenance does not indicate a need for maintenance and the production process parameters look adequate, but the production process output is not adequate, this is an indication that maintenance is needed now or soon (i.e., reactive) if the process cannot be adjusted by changing the production parameters to restore the output quality wanted. Thus, the continuous quality control can be used as an additional indicator for maintenance need, which may also involve a check-up and verification of the monitoring sensors and their function. Further, these two concepts can be integrated into the same data collection/monitoring/analytics platform, as they are both based on using sensor data combined with additional data, which is modeled in order to obtain input for decisions (suitably visualized to be understandable) and to enable warnings/notification as well as potentially automatic shutdowns or graceful degradation schemes in case serious problems occur but are not adequately predicted.

This paper addresses the question as to whether combining and integrating online predictive maintenance and continuous quality control can lead towards intelligent and sustainable production within the manufacturing industry. Further, the purpose is to make senior management teams and R&D managers aware of the potential of this approach and how it can be addressed. In addition, besides providing vehicle components, Gestamp HardTech AB is interested in providing "soft parts" and production equipment (mainly press-hardening equipment) as integrated product-service offerings or as Product-Service Systems (PSS) [1-2] or Functional Products (FP) [3-4]. This paper concerns an important aspect of achieving this.

The paper is organized such that the research approach follows the introduction and related work. This is followed by the result section including an analysis and, finally, the discussion and conclusions section.

2. Related work

There is a lot of existing work pertaining to predictive maintenance and quality control, and an open search using Google Scholar with the search string "predictive maintenance"+"quality control" limiting results to after year 2000 renders approximately 2470 hits. Limiting the same search to results after year 2010 renders approximately 1500 hits, and thus it is hard to assess if all relevant literature has been covered in the literature review. However, Lee et al. [5] posit that for service innovation and smart analytics, within the frame of Industry 4.0, there are 5 issues not yet adequately resolved: *manager and operator interaction* (where the health condition of machine components is missing), *machine fleet* (and gathering information/knowledge about all instances), *product and process quality* (feedback loops to the system are required), *Big Data and Cloud* (cloud capabilities required for self-awareness and self-learning machines with adaptive prognostics and health management), and, finally, *sensor and controller network* (where sensor failure/degradation can lead to wrong input to prognostics and, subsequently, incorrect outcome and decisions). This paper attempts to address all five of these issues; however, the last one to a lesser extent. The issues are addressed by outlining a scalable and generalizable online predictive maintenance and continuous quality control approach for production processes and equipment by collecting, modeling and analysing data originating from sensors or other data extractors, and also involving cloud solutions to support decision-making. Other research of interest includes: Cassady et al.'s [6] initial work on predictive maintenance and quality control, Lee et al.'s [7] conceptual work on intelligent prognostic tools and e-Maintenance (including proactive maintenance), Deloux et al.'s [8] outline of a predictive maintenance policy based on combining statistical process control and condition-based maintenance, and Duffuaa et al.'s [9] proposed conceptual simulation model for maintenance systems. The majority of the research listed is conceptual and only some of it is verified in industrial settings. Further, additional work of interest includes Koc et al.'s [10] introduction to e-Manufacturing including intelligent maintenance systems and e-Maintenance, Choudhary et al.'s [11] work on data mining in manufacturing, which includes both maintenance and quality, and Löfstrand et al.'s [12-13] and Reed et al.'s [14-15] work on simulation of maintenance, service and availability. This set of research brings in other areas of concern for predictive maintenance and continuous quality control and, in some cases, the latter are relevant to the other areas as well.

3. Research approach

The research approach employed in this study has been based on an indepth qualitative study using action research with a manufacturing company, Gestamp HardTech AB, located in northern Sweden. However, it would also have been possible to use a spiral model with gradual refinement for the research as well. Gestamp HardTech AB is part of the global Gestamp Group, which produces parts for vehicles and is active in 20 countries with 12 R&D centers, approximately 100 production plants and 32,000 employees. Gestamp HardTech AB has an R&D center, press-hardening tool development and manufacturing, as well as a production plant. The research targeted in this paper is the first phase and part of the second phase, i.e., diagnosing and planning action, of an action research [16] effort where the researchers have had the roles of external expert/consultant and internal expert. A literature review was part of the first phase and its result was used as input to the diagnosis. Action research has been defined as "*a participatory, democratic process concerned with developing practical knowing in the pursuit of worthwhile human purposes, grounded in a participatory worldview which we believe is emerging at this historical moment. It seeks to bring together action and reflection, theory and practice, in participation with others, in the pursuit* *of practical solutions to issues of pressing concern to people, and more generally the flourishing of individual persons and their communities*" [16]. The characteristics of action research are: (1) that action researchers act in the studied situations, and (2) that action research involves two goals. The goals pertain to solving the problem (the role of the consultant) and making a contribution to knowledge (the role of the researcher); further, that action research requires interaction and cooperation between researchers and the client personnel and, finally, that action research can include all types of data gathering methods [17]. In accordance with [18], the action research approach encompasses 4 phases: diagnosing, planning action, taking action and evaluating the action in relation to a certain context and with a specific purpose. Thus, the first phase and part of the second phase were completed with an iterative and reflective case management methodology. The data pertaining to the first phase, i.e., technical and organizational needs for change, were collected during 4 workshops [19] (involving 4-6 key respondents from the R&D, production and maintenance departments at each workshop) and 3 semi-structured open-ended interviews [20-21] with key respondents (i.e., R&D manager, manager tool design and development and senior researcher/development engineer). The workshops and interviews were conducted from late 2014 until late 2016. The respondents were well aware of and knowledgeable regarding production systems/equipment, predictive maintenance and quality control as well as integrated products-services, PSS and FP.

Gestamp HardTech AB has its roots in hardware development and production, and its set of special competencies comprises: press-hardening techniques and technology (creator of original patent SE 7315058-3), simulation-driven design and just-in-time logistics. However, additional complimentary components have been added to its customer offerings. Further, Gestamp HardTech AB aims to increase its global revenue from soft parts; i.e., services, knowledge or know-how as well as advanced offerings based on, for instance, integrated products-services, PSS or FP.

To collect data after the workshops semi-structured interviews with open-ended questions [20-21] were used, allowing the respondents to give detailed answers and the possibility to add extra information where deemed necessary [22]. The duration of the interviews was between one and two hours. In order to reduce response bias, the respondents came from various parts of the organization as well as different levels i.e., strategic, tactical and operational units. In order to strengthen the validity of the study, data were continuously displayed using a projector during the interviews, allowing the respondents to immediately read and accept the collected data. After that, the collected data were displayed and analyzed using matrices (cf. [23]) and the outcome of the planning action efforts summarized into causal relational graphs (cf. [23]). The analyzed data were finally summarized into two matrices comprising the diagnosis in terms of technical and organizational needs (see Tables 1 and 2) as well as a high-level plan for action related to technology (see Figure 2).

The first initial design criterion for the combination of on-line predictive maintenance and continuous quality control was that it should be simplistic and have a low implementation cost and be inexpensive to use and maintain over time (in comparison with existing solutions for either of the concepts on the market). Further, the second initial design criterion was that the outcome should be a solution that can operate online close to real-time, i.e., with seconds or parts of seconds in response time, but not in hard real-time mode with requirements on millisecond level. The design criteria will not be formally evaluated (as the action has not yet been taken) in this paper but discussed in the last section of the paper in order to judge if the outcome will lead "towards intelligent and sustainable production".

4. Towards intelligent and sustainable production at a vehicle component provider

The overall production process at Gestamp HardTech AB is depicted in Figure 1 and comprises a number of sub-processes, e.g., blanking, press-hardening and post operations. An ERP-system sends production order data to all sub-processes based on customer orders. If it is possible to measure and analyze data generated from all sub-processes, a number of measures which improve quality and maintenance could be achieved. That would allow for a continuous quality control, i.e., production process/sub-process parameters and measured output feedback in order to make process adjustments, as well as online predictive maintenance of production equipment in order to be able respond proactively instead of reactively. The continuous quality control can also indicate the need for maintenance. Additional effects wanted are: time savings (faster production process flow), lower cost for materials (less waste and scrapped output) and lower cost for energy (less scrapped output and operation runs more smoothly and optimized), fewer time/cost/energy-consuming post operations required, improved trust in the production process (thus allowing higher calculated risks in terms of tougher and demanding orders), avoidance of total stops in the production process, as well as the ability to detect bottlenecks.

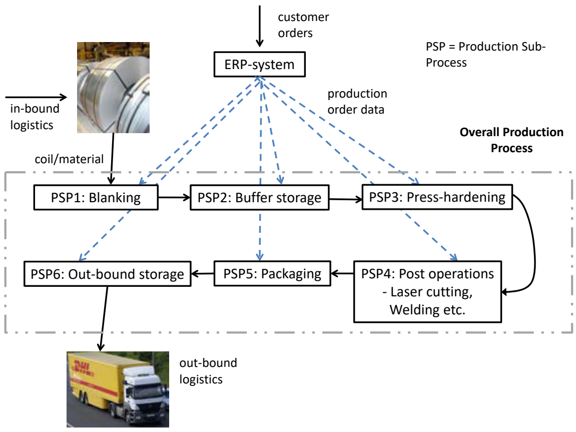

Fig. 1. Overall production process and sub-processes.

During the diagnosis phase, the needs for technical and organizational changes were revealed and collected. These are listed below in Tables 1 and 2, and prioritized according to 10 (high) and 1 (low) need.

Table 1. Diagnosis - need for technical change.

Technical issue or need	Priority
1.) Provide turn-key, integrated product-service or functional solutions (press-hardening equipment) to internal as well as external customers – this requires that the equipment can be monitored and maintained proactively by use of online predictive maintenance techniques and methods. Further, this requires new equipment design in terms of adding sensors to measure and follow what happens in the equipment. Also, there is a need to remotely access the equipment and its monitoring data collected and be able to take (some) measures from distance.	5
2.) Need to better be able to continuously monitor the production process quality (i.e., that the process parameters are within expected ranges and the production output meets the desired quality criteria).	9
3.) The solution should be as simple as possible and have low cost to implement, operate and maintain.	4
4.) The solution should be robust and future-proof.	8
5.) Can the online predictive maintenance and continuous quality control concepts be combined in order to minimize the number of solutions/services in the production process?	6
6.) Are there any additional concepts that should be included/combined as well?	4
7.) Is hard real-time response necessary? It is predictive maintenance and continuous quality control of a production process that has a process step of more than a few seconds.	5
8.) We want an information model and data/parameter modeling in order to better understand the production equipment and be able to predict problems/maintenance need.	9
9.) We want to use data mining techniques in order to find new unrevealed important relations in between the data collected – to enhance the prediction of maintenance need as well as improve the quality of the production process and its output.	7
10.) Can we make the production process "self-learning" to avoid production stops or quality problems?	4
11.) How much faster can we find out where the problems are and also the root causes? Should be fact-based. Need to minimize stop time and avoid the same issue again where possible.	8
12.) How can we improve the production process and its equipment? The improvement should be based on the data collected and analyzed.	8
13.) How, as well as how much, can the maintenance efforts and costs be optimized/minimized at the same time as the production process availability is maximized?	3
14.) How can we improve the output quality from the production process?	9
15.) How can energy consumption be optimized/minimized?	7
16.) How, as well as how much, can the production equipment lifetime be extended/optimized?	3
17.) If we know the status of the production process and its equipment, i.e., have trustworthy health indexes, we can take tougher orders (and more production-related risk).	9

The technical issues and needs with a prioritization exceeding 6 were passed on to the next phase action planning.

Table 2. Diagnosis - need for organizational change.

Organization issue or need	Priority
1.) Regarding the business model, a win-win situation must be sustainable over time when offering and selling advanced/ complex offers to internal as well as external customers.	8
2.) Need to learn more on advanced/complex business models and further analyze how they affect us as an organization and the long-term business. Involves everyone from top management to shop floor and, in particular, the sales teams.	5
3.) The organization needs to start to think in new ways and take in ideas about new concepts, models, methods and techniques.	7
4.) In the production and maintenance teams we may need more personnel with higher education and analytic skills in order to find problems/root causes by analyzing the equipment and large/complex data sets.	8
5.) We will need new skills/competencies such as: mechatronics, programming, computers/hardware devices/cyber-physical systems, analytic software and methods, data mining, as well as engineering (mechanics, production, maintenance, electronics, communications, etc.).	9
6.) We need to be able to convert tacit knowledge (know-how) to formal (codified) knowledge in order to provide professional training to more personnel involved as well as improve workplace flexibility. Need to only add verified knowledge.	5
7.) In order to attract creative and competent/experienced personnel, our workplace and job descriptions need to be creative/attractive.	7

The organizational issues and needs with a prioritization exceeding 6 were also passed on to the next phase.

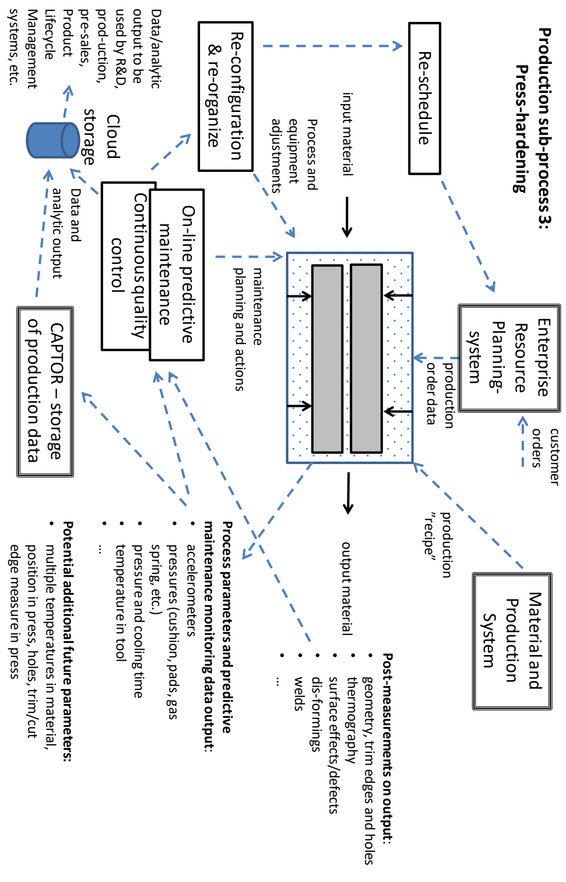

Fig. 2. High-level plan for action regarding technical change of the press-hardening sub-process and its equipment.

The high-level plan for action regarding technical change of the press-hardening sub-process and its equipment is outlined in Figure 2. The action planning for the organizational issues and needs diagnosed will be finalized later.

The technical change will enhance the possibility to quickly re-configure and re-organize the sub-processes to respond to quality variations as well as facilitate production of smaller batches and quicker re-scheduling of production plans with retained high-quality output. An example of re-configuring is to quickly be able to adjust the hardening and cooling, based on measured data, to avoid quality variances or inadequate quality. Further, an example of re-organizing is to add additional process steps or replace malfunctioning production equipment. In addition, if certain problems are not possible to solve via re-configuration or re-organizing, the production schedule may need to be re-organized in order to produce the output that is possible under the actual circumstances.

The plan for action (Figure 2) outlines the schematic information flow between the involved artifacts, systems and equipment involved in the production sub-process 3 (press-hardening). Based on this plan, a high-level concept and detailed architecture will be crafted in the following phase where action is taken, prior to an information model being developed. Based on the information model and knowledge about the production process and press-hardening equipment, data/parameter modeling will be conducted in order to facilitate qualitative and quantitative analytic approaches. Online data will be combined with stored data (internally and in the cloud), meta-data, derived data, data from other databases and vendor databases/webs, etc. An example is the virtual product representation that exists in the Product Lifecycle Management (PLM) system that can be used as a digital twin of the press hardening equipment, enabling a bilateral connection to design data [24], thus creating a tightly integrated PLM solution [25]. Further, fusion of data and additional data mining techniques will be applied to reveal relations in between data and parameters not already known. In order to increase the accuracy of the predictions and quality control, the intention is to use triangulation of methods and data where preferably more than two separate ones/relations indicate the same issue or problem. Self-learning analytic algorithms may be applied and used where clear value can be added by such.

4.1 Analysis

Concerning Table 1 and the prioritization level exceeding 6, the following entries were selected: 2, 4, 5, 8, 9, 11, 12, 14, 15 and 17. Out of these, entries: 2, 8, 14 and 17 were assigned a prioritization of 9 and are thus the most prioritized of all. Of interest among the ones that were not selected is 3 – which leads to a necessary update of the first initial design criteria as robust, high output quality and future proof. This shift is interesting and a consequence of the foreseen ability to improve revenue and customer satisfaction more than being able to keep the costs for software, etc. low.

Concerning Table 2, the entries with a prioritization exceeding 6, i.e., 1, 3, 4, 5 and 7 will be passed on to the action planning.

5. Discussion and conclusions

The paper makes a contribution to literature by combining and integrating online predictive maintenance and continuous quality control in an action research effort. The continued action research efforts will plan the remainder (i.e., the organizational part), take action and then evaluate the action. Further, the paper contributes to practice by outlining how the diagnosis and action planning can be done, which may be of interest for manufacturing and process industry companies with the need to address both matters (and perhaps additional matters possible to combine and integrate). The managerial contribution of the paper is to highlight the opportunity of combining and integrating two or more concepts based on the same principles as well as what effects can be expected from doing so. To minimize complexity, costs and increase/maximize the effects at the same time ought to be attractive for many organizations.

The research so far, comprising the first phase and part of the second, has already resulted in new requirements added for new generations of press-hardening equipment in terms of: additional sensors to enable monitoring, new industrial computers and cabling/data buses/communications, as well as improved reliability for hardware components, improved maintainability and means to remotely monitor and take some service/maintenance actions. As the action research effort progresses, an increasing understanding of the organizational matters related to the technical ones has become evident. It is clear that the technical change needs to go hand in hand with the organizational change. The organizational change will likely take more effort to implement, for instance, requiring change in behavior and acquiring additional skills and competencies, as technical change is easier to initiate and accomplish.

Regarding the design criteria, it became clear that the first initial one needed to be updated as more insight and details were gained. From being focused on simplicity and low cost to implement, use and maintain over time, it shifted instead towards being robust, having high output quality and being future-proof. To have a high output quality was deemed the most import. The updated first design criteria will together with the second design criteria pave the way towards an intelligent and sustainable production at Gestamp HardTech AB and potentially other organizations as well.

If wanted or necessary, it will be possible to combine and integrate additional concepts in the future. However, that requires that the additional concept adds value and can be added in a reasonably efficient manner without complicating the whole. Examples of such future additions are data stream mining/analytics and artificial intelligence (AI) that can be used to get closer to real-time and improve the depth of the data mining and improve the support for decisions. Further, notification/warnings, improved visualization and further intelligent decision-making support will be of interest when continuing the action research effort. Lastly, since design data, such as CAD drawings, simulations and specifications, are often available in a PLM system, this information can be used to track individual equipment as well as production output to provide traceability and statistics for a whole fleet of equipment within an enterprise. It also enables traceability from the first design data received from customers to each individual component delivered to the customers.

Finally, efforts like the one described and depicted in this paper are necessary for many manufacturing companies to stay competitive, efficient, intelligent and sustainable.

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