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The Means to Achieve a Digital Transition of Manufacturing Shop Floor

John Bang MATHIASEN[a,1] and Pernille CLAUSEN [b]
[a] *Aarhus University, Denmark*
[b] *Aalborg University, Denmark*

Abstract. The digital transition of manufacturing shop floors makes topical an empirical study of designing a cybernetic system to monitor and control the performance of smart manufacturing. This paper uses Transdisciplinary Design Science (TDS) to explore how a company producing large products designs and evaluates a cybernetic system providing the needed functionalities to monitor and control an unpaced manufacturing line. TDS involves an exploration of a solution, designing the cybernetic system, followed by an explanatory elaboration of theories. By studying the exploration and explanation through the lens of the means-end-analysis the paper shows that the means to enable a digital transition of the manufacturing shop floor have a transdisciplinary nature; the transfer of means across disciplinary boundaries is either to translate or transform.

Keywords. Transdisciplinarity, Cybernetics, Digitalisation, Smart Manufacturing

1. Introduction

The digital transition of companies entails that shop floor practitioners operate highly computerised manufacturing equipment. Digitalisation enables smart manufacturing to collect, store, retrieve, and visualise data [1], which paves the way for providing practitioners access to digital information in real-time [2]. However, practitioners are forced to rely on analogue dashboards when handling malfunctions or variations within manufacturing [3], which makes topical an empirical study of designing a cybernetic system [4] to monitor and control a smart manufacturing set-up [5].

The means to design a Cybernetic Monitor and Control System (CMCS) providing the needed functionalities embraces both academic knowledge and practical knowledge [6], which calls for a transdisciplinary approach [7]. At the outset of this study, we gradually acknowledge that scientific articles on smart manufacturing are fragmented and decoupled from the physical reality at the shop floor level. We noticed that most companies still apply non-digitized systems and attach various printout documents manually on dashboards. A stream of researchers suggests that non-digitized systems enhance usability. These researchers bring *social means* to the fore such as the power of the pen [8], that is, to use non-digitized systems rather than software-based systems [9], provide easy-to-understand information [10], and recognize the importance of having brief meetings [11]. However, another stream of researchers subscribes to the digital turn [cf. 12] and hence foregrounds *technical means* [13; 14]. These researchers claim that non-digitized systems only depict historical data and do not enable cross-boundary

[1] Corresponding Author, Mail: johnbm@btech.au.dk

worker interaction. Likewise, computerised manufacturing equipment generates real-time data and reliable data [5]. This, in combination with emerging machine learning [15] and artificial intelligence systems [16], paves the way for offering practitioners a CMCS to manage the shop floor.

Despite the digital transition of manufacturing equipment and information technologies have been on track for more than 40 years neither researchers nor practitioners have yet clarified *the means to reach the desired state*; in this study, the desired state would be a shop floor CMCS that provides practitioners with the needed functionalities to manage smart manufacturing shop floors. This study of designing a CMCS commences with three warrant assertions. First, the means embrace academic knowledge and practical knowledge, second the means are both social and technical, and third a Transdisciplinary Design Science (TDS) research seems appropriate [6]. These warrant assertions motivate us to put forward a working hypothesis [17], suggesting that "*researchers and practitioners do not seize the transdisciplinary nature of means to design a CMCS having the needed functionalities*". Accordingly, the study aims at exploring the best explanation [18] of the working hypothesis, and at examining how a company can align the functionalities of a CMCS with a smart manufacturing context. We reflect upon the research question "*what means if any can enable the design of a CMCS providing the needed functionalities?*" in a global manufacturing company. The company belongs to the renewable energy industry. The products are large, and the manufacturing occurs in an unpaced product line.

Methodologically, the research draws on a TDS approach [6]. Because TDS unfolds as border-work [19] and the fact that the understanding of the problem and the design of the solution are jointly framed [20] entails that the means to reach the desired state transcend disciplinary boundaries. To analyse the extent to which the means are transcending disciplinary boundaries we draw on the means-end-analysis [21].

2. Smart manufacturing shop floor and cybernetics system

A smart manufacturing shop floor generates a continuous stream of big volumes of data [1]. Data generated by planning applications combined with traceability systems consisting of electronics, sensors, RFID tags, and embedded systems in the manufacturing equipment are pivotal for the functionality of a CMCS to manage both the flow of material and the performance [cf. 2]. This study conceptualises a CMCS as a sociotechnical configuration, which embraces the application architecture-practitioner reciprocity [4]. The application architecture determines the accessibility of data to the CMCS, which includes interoperability and automation of data lifecycles [cf. 13]. As knowledge is embodied and situational [17], the visual interfaces between the application architecture and the practitioners affect the usability of the CMCS to convert data into information, convey information into visual meaning, visual meaning into embodied knowledge, into common knowledge, and into actions.

2.1. Background of the study

The industrial rethinking represented by Industry 4.0 [cf. 22] including the exponential development of digital technologies [23] paves the way for various technical means to harvest the benefits of the digital transition towards a smart manufacturing set-up [5]. Proper use of these technical means can eliminate information silos [24] and can enable real-time access to big data [25], and the use of machine learning [15] and artificial intelligence [16] can provide the needed functionalities to monitor the performance and progress across manufacturing shop floors [26]. However, these researchers focus on enhancing the accessibility of data and information, but they refrain from design guidelines to ensure appropriate usability of the visualised data on the CMCS.

The fundamental design to enhance the usability of visualised data originates from the principles of the Toyota Production System [27] and thus Lean [28]. This mindset can be traced back to the mid-1940s [27] implying that the means to guide the design of a shop floor cybernetic system are stuck in the I.2.0 era [29]. The viewpoint is that the handling of shop floor tasks progresses as social interactions [29] and that the visualisation of data is the glue for social interactions [30]. These means to design such a system highlight the power of the pen entailing the use of a non-digitised approach rather than a software-based approach [10]. The non-digitised approach enhances team communication and problem-solving capabilities [8], and display easy-to-understand information [11] which is valuable for achieving shared understanding across professional disciplines [9]. The following section presents the analytical framework to explore the means to design a CMCS.

2.2. Analytical framework – means-end-analysis

When practitioners and scientists in symbiosis are involved in exploring potential solutions to a complex problem, such as designing a CMCS, their individual actions enter into the relationship between the means and the end [6; 17; 21; 32]. The end is the desired state for each of the involved individuals. The means are instrumental in transforming the current state into the desired state [17]. Means acquire meaning when practitioners and scientists deliberately applied the means to reach the desired state and the outcome of being involved in these activities is embodied knowledge [6].

The individuals' perceptions of the desired state differ [17; 33]. To reach the desired state the means, in the form of embodied knowledge, should transcend boundaries – academic, professional, organisational, and so on. For this reason, both scientists and practitioners need to cope with the perception of others, i.e., their different perceptions of both the current state and desired state. To gain a common perception of both the current state and the desired state, the involved scientists and practitioners should be capable of sharing embodied knowledge [34]. As knowledge is embodied and situational [17], the "transfer" of embodied knowledge is not straightforward. As Gherardi and Nicolini [35] remind us "to transfer is to translate or to transform".

3. Research design

When embarking on this study we realised that the prevalent literature on manufacturing shop floor VBs either focuses on social means to enhance the usability of a CMCS or technical means to enhance interoperability and automate the data treatment throughout the whole data lifecycle. This in combination with the practical realities on the shop floor entailed that we faced an ill-structured problem in terms of designing a CMCS. TDS is a useful research approach to address ill-structured problems [6; 36] in an organised way [37], especially when practitioners' perceptions of the problem and potential solutions conflict with those derived from widely accepted theories [38].

The transdisciplinary setting for exploring the working hypothesis and the research question is a global company developing, and manufacturing renewal energy products (designated Alpha in this study). In April 2020, Alpha involved us in an intervention project requiring both academic knowledge, practical knowledge and knowledge transcending various professional disciplines. The purpose was to design and implement a CMCS to comply with takt-time requirement in unpaced manufacturing lines.

In TDS research, the solution must be explored before elaborating on theories [6]. It entails we commence with exploration followed by an explanation [32]. As it appears from table 1, the exploration is divided into three phases, which are (i) exploration of the current state and the desired state, (ii) exploration of the means to reach the desired state, and (iii) exploration of the actual state – test and evaluation of the designed CMCS.

Table 1. The three phases of exploration. Source: Mathiasen and Clausen, forthcoming

Exploration of current state and desired state	Exploration of means to reach the desired state	Exploration of actual state: Test & Evaluation
Observations of takt-time shop floor meetings: • 14 online • 10 onsite **Semi-structured interviews:** • 5 online • 6 face-to-face **Informal, unstructured interviews:** • 10+ face-to-face Presentations: •2 online presentations with the purpose of agreeing upon current state **Current state report:** •Draw up a current state report •Hand in the report in May 2020	**Informal, unstructured interviews** • 20+ face-to-face **Semi-structured interviews:** • 15 online • 7 face-to-face **Active participation in workshops:** •4 online; inputs to solution •1 onsite; inputs to solution **Project meetings, international:** •30+ online; status and coordination •3 online; presenting solution proposals **Report:** •Proposed framework for a solution •Technical web-based solution enabling interoperability	**Observations of takt-time shop floor meetings:** • 2 online • 4 onsite **Semi-structured interviews:** • 3 online interviews • 4 face-to-face **Project meetings – international:** • 2 online; planning field test and minor redesign of the implemented solution **Actual state report and presentation** • Draw up evaluation report, June 2021 • Draw up evaluation report, January 2022 • 1 onsite presentation of field test and evaluation • 1 online presentation of field test and evaluation

Each of the three columns accounts for our involvement within Alpha and thus the data collection for this TDS research. The project team permitted one of the authors 24/7 access to manufacturing facilities and a desk in the open-plan office. This paved the way for (i) an outstanding opportunity to follow and be proactive in the design of the CMCS, (ii) 30 observations of takt-time shop floor meetings, (iii) 40 semi-structured interviews and more than 30 informal unstructured interviews, (iv) active participations in 5 workshops and more than 35 project meetings, (v) draw-up and present a current state report, and a framework for a solution, a technical web-based solution enabling interoperability, and two field test evaluations reports. Please notice, owing to the Covid-19 pandemic and the international composition of the project team, it was necessary to carry out some online interviews and observations.

The exploratory phase puts a laser-like focus on the means-end relationship. Because knowledge is embodied and embedded in different professional disciplines be it academic and/or practical the means to reach the end transcend disciplinary boundaries. Our means-end analytical framework paves the way for clarifying the extent to which the means should be translated or transformed. In the exploration of the current state and the desired state, the focal point is to gain an understanding of the extent to which the functionalities of current analogue VBs are means for practitioners to handle shop floor tasks. In the second phase, the analytical focus is to reveal the means to design a CMCS providing the needed functionalities – the means to reach Alpha's desired state. In the third phase, we are keen on understanding the extent to which the functionalities of the designed CMCS function as means for practitioners to handle shop floor tasks.

The findings from the above three exploratory phases make up the foundation for our explanatory analyses in which we intend to elaborate theories. We accomplish two kinds of means-end analyses. First, the centre of our reflections is the extent to which practical understanding (knowledge) of the problem and potential solutions gainsaid prevalent theories. Second, the focal point of our reflections is to examine and thus elaborate on how to combine theories concerning the usability of a CMCS with theories enabling the digital transformation of manufacturing companies.

4. Exploration of the current state and desired state

Alpha operates with a 9-hour takt-time in an unpaced synchronous flow line [39]. The manufacturing comprises five workcells, all using non-digitised takt-time dashboards. Each workcell consists of several workstations. Shop floor tasks to ensure takt-time compliance revolve around monitoring variations in the flow of materials and coping with these variations. Alpha accomplishes two types of takt-time meetings, one within each workcell and one across the workcells. Alpha applies the non-digitised takt-time dashboards to accomplish two daily shop floor meetings in all workcells. Our findings show that physical proximity is a prerequisite for transcending disciplinaries boundaries. Accordingly, because of 1.5 kilometres distance between workcell one and five and the use of non-digitised dashboards forces the practitioners to accomplish the across workcell meetings without using and dashboards. In general, the non-digitised dashboards provide functionalities to transcend disciplinary boundaries as long as the involved practitioners stand close to the dashboard and each other.

A CMCS that affords practitioners to comply with takt-time requirements within and across all five workcells would be the desired state. The project team reveals eight functional requirements, which should afford practitioners to (i) accomplish onsite/online takt-time meetings, (ii) adapt displayed data/information to the shop floor tasks being handled, (iii) monitor variations between planned progress and actual progress, (iv) comply with standard operating procedures, and (v) accomplish systematic root-cause analyses, (vi) gain access to real-time data and reliable data, (vii) gain access to historical data, and (viii) perform data analytics.

5. Exploration of means to reach the desired state

The complexity faced during this phase causes two sequential design projects: from now on design-1 and design-2. A Lean manager was in charge of design-1. The participants were Lean specialists, data specialists, workcell managers, and us. Given that the first project team was incapable of reaching the desired state a new project team was formed. A data scientist managed design-2; participants in this second attempt were data scientists, hardware specialists, software specialists, partly Lean specialists, and us.

Design-1 got off to a good start, but the project team ascertained important constraints in the application architecture six months after the launch of the project. The constraints were related to current manual data handling and interoperability, mainly between SAP and PRISMA. We (the two authors) suggested redesigning the application architecture which, according to [40], required both frontend development and backend development to (i) automate the whole data treatment process including collection, coding, storage, retrieving, manipulation, analysis, and visualisation of the data [see 13], and (ii) enhance the interoperability [see 41]. Specifically, the suggested means to remove the constraints in the application architecture were (i) automating the data collection process about worker's clock-in and clock-out on job orders and material movement downtimes, (ii) ensuring data storage and retrieval directly in SAP, (iii) enhancing interoperability by implementing a web-based Application Programming Interface (API), (iv) designing user-friendly interfaces to capture data and an adaptable layout on the interactive screen on the CMCS.

The project team gradually translated our proposed means to design the front end of the solution; the project team gained a common understanding of a usable layout on the interactive screen and sensors to enable data acquisition. However, the translation of the means to carry out the backend design of the solution to automate the data processing and the improvement of the interoperability was uphill as the project team was "*not allowed to make any changes in SAP …. and we have to apply PRISMA for entering production data*" (Project manager). Strict IT policies combined with stringent cyber security and data security [see 42] blocked the translation of the suggested means. For instance, all data collection should be handled manually or occur via PRISMA, and it was not an option to download data in SAP. While these constraints obstructed the translation of means to automate the data treatment, it seemed doable to translate our means to enhance interoperability.

We designed and wrote software to (i) an SQL database functioning as an information hub to access and store data from SAP, PRISMA, and applied sub-systems, (ii) a web-based API to inquire and retrieve data from the SQL database, and (iii) a web-based solution for visualising data on the interactive screen. The solution was a prototype and demonstrated usable functionality within a test environment. Despite the presence of a workable prototype the project manager rejected the proposed solution "*your API solution seems to be a good idea and it might be the only way for us to go, but it does not comply with our IT policies and information security …. Sorry to say this, but your solution borders on being too naïve….*". Neither our technical elaboration of the solution nor the demonstration of a workable solution could enable the translations of means, and at last, the project manager put design-1 on hold.

The Covid-19 pandemic caused the majority of all white-collar workers to work from home, which restarted the design-1 project. The restart of the project forced the project team to design a solution providing practitioners with online access to the CMCS in a rush. The management approved that the design did not comply with all the needed functionalities. The designed solution consisted of (i) a Microsoft SQL database acting as an information hub to access and store data from SAP, PRISMA, and various subsystems, (ii) the use of Microsoft's Power Apps paved the way for designing the interface layouts on the CMCS, and used to both retrieve data from the SQL database and to visualise data on the CMCS. The interface layout was broadly similar to the non-digitised dashboard. However, at the end of the day, top management formed a new project to design s solution fulfilling all needed functionalities. The following section elaborates design-2 managed by the data scientist.

Design-2 drew on the knowledge gained during design-1, which brought to the fore that central means to reach the desired state would be (i) automating the acquisition of data via web applications with regards to workers' clock-in and clock-out on job orders and the use of sensors and cameras to collect data related to material movement downtime, (ii) data storage and retrieval of data directly via the use of SAP or via the use of an Industrial-PC (IPC) and an SQL database, (iii) enhancing interoperability by designing a web-based API solution, including writing the needed software code, and (iv) adopting the interface layouts developed in design-1.

While knowledge about cyber security and data security was easily translated across the two project teams, the new project manager strove to transform the IT policy demanding the use of PRISMA for data collection. After some back-and-forth exchange of views, the top management accepted that. Accordingly, the acquisition of data and storage of data could be enabled without interfacing with the PRISMA application. However, PRISMA could not be replaced before the CMCS was field tested and fully implemented. This caused shop floor workers should carry out data registration twice. Despite this redundant data registration conflicted with Lean philosophy [11] and we also highlighted reluctance among blue-collar workers to carry out data registration twice, the other participants in the project team did not consider this as an issue. Apparently, something seemed to be at stake and consequently, our viewpoints did not transcend the disciplinary boundary.

Compared with design-1, design-2 concerned automating data collection and enhancing interoperability. As for the former, the project team designed and wrote software for two web applications to enable direct data storage in the SQL database via IPC and real-time data collection via interactive displays, i.e., data collection and storage without interfacing with PRISMA. The first web application made it mandatory for blue-collar workers to clock-in when beginning each production task and clock-out when ending the task. This, however, would increase the number of registrations. The second web application forced managers to instantly record any kind of interruption in the material flow (deviations and causes). The means to enhance interoperability involved (i) developing and thus using an SQL database as the information hub to store data from the two designed web applications and to gain access to data from SAP and various subsystems, mainly Excel and SharePoint files, (ii) developing a web-based API to inquiry data and to retrieve data from the developed SQL database, and (iii) developing a third web-based application to visualize data on the digital takt-time interactive screen.

6. Exploring the gap between the desired state and actual state: test and evaluation

Design-1 underwent the test and evaluation during the Covid-19 lockdown. At present, the practitioners have applied the designed CMCS for more than two years, that is, both during and after the pandemic. The accomplishment of the test was the manufacturing shop floor. The test proved that design-1 provided online access to the CMCS and a camera attached to the interactive screen enabled online access to shop floor meetings. The CMCS functioned as means to: (i) transcend disciplinary boundaries *"....online access was paramount for us during the lockdown* [Covid-19 lockdown] *and now we have realized that it reduces the wasted time during the meetings.... plant takt-time meetings are more effective now as we have access to all takt-time dashboards across our workcells*" (Workcell Manager), (ii) adapt the displayed data to (a) comply with the standard operating procedures and thereby accomplish effective shop floor meetings both within and across all five workcells, and (b) to the tasks being handled which seemed useful to gain a common understanding of the faced problem and to carry out systematic root-cause analyses, which led to "*ad-hoc involvement of a specialist is much easier now .... all workers are more open-minded"* (workcell manager) *and "the workers are more proactive during the meetings*" (Lean manager), (iii) automatically update planned progress, but a practitioner should update the actual progress manually, and (iv) partly access historical data; only retrievable data from the Microsoft SQL database could be displayed. These historical data provided practitioners to "*recall how we previously handled malfunctions*" (workstation manager). Furthermore, the Lean manager declared *".... having direct access to historical data makes it possible to analyze trends such as the number of malfunctions in workstations*".

The test demonstrated that the CMCS did not function as means to: (i) provide practitioners access to real-time data or apply machine learning algorithms to conduct data analytics and close feedback loops. Instead, practitioners could apply Excel to carry out simple data analytics, and (ii) avoid the manual registrations of downtimes and the workers' clock-in and clock-out on job orders causing low reliability of data.

Design-2 was subjected to both a Beta test (in a test environment) and a field test, which however demonstrated completely different outcomes. In a testing environment, the project team demonstrated that design-2 provided all eight desired functionalities: (i) the interactive user interface and the designed web applications enabled workers to clock in and out and workstation managers to register delays (downtime and causes), (ii) data could be coded and stored correctly in the database. Data could be retrieved and displayed on the interactive takt-time screen; the displayed data was adaptable, (iii) the systems automatically updated both planned progress and actual progress on the interactive screen including the reason for a delay: actual delay marked red, expected delay marked blue, and marked yellow when workcell(s) had finished all tasks but downstream issues made a movement impossible, and (iv) data could be exported from the SQL database to Power BI and thereby accomplish data analytics. Intervention-2 provided all eight functionalities within a testing environment.

Design-2 afforded the desired functionalities, but the accomplished 24-hour field test on the manufacturing shop floor over two shifts showed that: (i) the two appointed workstation managers lacked the knowledge to supervise the field test as "*we only got a brief introduction to the test and he* [the project manager] *did not inform us how to evaluate the test….the workers did not understand how to register data….and they could not understand why to do the registration twice*." (workstation managers), and (ii) the capture and storage of data malfunctioned. Despite some data being captured and stored in the database, the data foundation did not allow us to evaluate the extent to which design-2 provided the desired functionalities.

Basically, design-2 clashed with the practical realities on the shop floor. On the one hand, the inadequate capture and storage of data could be caused by inflexible workers, who eschewed carrying out double registration of data. On the other hand, which seemed more likely, the project team ignored usability means. For instance, in addition to the double registration issues, the project team neglected the practical realities across the five workcells. The requirement for data registration across the workcells differed; instead of customizing the interfaces, the project team designed a one-size-fits-all user interface.

7. Explanatory analyses and discussions

The exploratory analyses enable us to put forward our best explanation [18] to the working hypothesis "*researchers and practitioners do not seize the transdisciplinary nature of means to design a CMCS having the needed functionalities*." As demonstrated in the background for this TDS research, the scientific literature is both fragmented and decoupled from the manufacturing shop floor. Researchers either concentrate on putting forward technical knowledge to enable a smooth digital transition thus neglecting the usability of the CMCS [cf. 13] or the researchers focus on usability and accordingly refrain from addressing issues related to the digital transition [12]. In the same way, because the practitioners ignore the importance of border-work [19], neither design-1 nor design-2 did successfully develop and implement a CMCS providing all needed functionalities. The actual state of design-1 was a CMCS, which did neither provide functionalities to access real-time and reliable data nor to conduct data analytics, and practitioners should still carry registrations of downtimes and clock-in and clock-out on job orders manually. The design-1 project team did not acquire sufficient technical knowledge to articulate the constraints in the current application architecture and even more problematic, the project manager applied Alpha's IT Policies to block a common understanding of the transdisciplinary nature of means to enable the design. The actual state of design-2 was a successful accomplishment of the Beta test, but the field test proved an unworkable solution. The project team had sufficient knowledge to elaborate on the technical constraints within the current application architecture to bend the IP Politics. However, throughout design-2 the project team ignored both issues related to the usability of the CMCS and practical matters on the shop floor.

To reflect on "*what means if any can enable the design of a CMCS providing the needed functionalities?*" we address the extent to which the practical understanding (knowledge) of the problem and potential solutions gainsaid prevalent theories, and how to combine theories concerning the usability of CMCS with theories enabling the digital transformation of manufacturing companies. In general, practitioners have sufficient knowledge or have the capabilities to use theories to ensure a translation of means across disciplinary boundaries. However, this TDS research reveals some situations where the involved practitioners face disciplinary siloes, such as when rephrasing/changing IT policies, redesigning the application architecture, or changing the usability of a digital solution leading to new working practices. These practitioners understand the requirement for changes, but they struggle with realising that the border work should be a give-and-take endeavour – in other words, the willingness to accept some of the other practitioners' ideas and give up some of your own. When trapped in such disciplinary siloes the prevalent theories of smart manufacturing is too fragmented to guide practitioners to transcend the disciplinary boundaries. Both practitioners and researchers will benefit from subscribing to the viewpoint that the means to enable a digital transition of the manufacturing shop floor have a transdisciplinary nature; the transfer of means across disciplinary boundaries is either to translate or transform.

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