Overview on the digitized production of welded steel structures

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Abstract

This paper presents a concept and practical topics involved in digitized production. The term “production” denotes the design, fabrication, and service life of a product, which in this case elaborates on welded steel structures. This includes the required information for guiding all the process stages of the chosen material back to its re-melting, following the material flow in a fully digitized form. This concept enables an increase in production quality at a higher level while minimizing the risk of human errors. Automation of the short-run production of steel structures for demanding applications is also a key goal, together with securing a cost-efficient process. Typically, such structures are fabricated from high- or ultra-high-strength steels. Though challenging, reaching these aims seems to be realistic by applying advanced fatigue design methods, using high-quality robotic welding and receiving information about the real loading of the structure.

Keywords Digitized production · Design and fabrication · Welded structures · Ultra-high-strength steel

1 Introduction

The fourth revolution of industrial manufacturing processes, known as Industry 4.0, has enabled steps towards the usage of information technology and systems in the manufacturing processes. Industry 4.0 has also challenged conventional manufacturing technologies, such as welding technology, to find new solutions for utilizing information and data acquisition in welding production. For instance, adaptive and artificial neural network-based solutions to control welding processes and automatic quality assurance systems to verify the accomplishment of a required quality level [1] have emerged in recent years. General level production control and product management systems and software are widely adopted in workshops. However, there are also other factors driving us towards the digitized welding production. It has been

estimated that in 2018, the steel industry produced 7–9% of global direct emissions induced by the use of fossil fuels [2] and, thus, actions taken in this sector are important. A need for reducing emissions in steel constructions, as a part of active climate actions, has excitably led to the structural and material usage optimizations. The means of the optimizations incorporate the design of welded components targeting on increase in the degree of capacity utilizations, which claims a higher precision and novel methods in structural analyses to account for the welding quality.

Recently, use of high- and ultra-high-strength steels (HSS/UHSS) has received both academic and engineering interest to aim to weight and cost reduction in structural components [3–5]. Prior studies, however, have clearly indicated that welding as a joining method can severely modify the high performance of parent UHSS materials. Welding of HSS and UHSS materials may incorporate several issues, such as a reduced static strength [6, 7], ductility [8–10], and fatigue strength [11], as well as brittle failure susceptibility [12] and structural stiffness. These aspects demand a careful consideration of optimal process parameters, together with potential pre- and post-weld treatments, as well as advanced design phase to maintain the good properties of parent material, resulting in an increased amount of information needed in the fabrication. On the other hand, modern business models have shifted towards service- and outcome-based models, including a product, maintenance, and repair, instead

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of product-based business activities. Consequently, product history data and specification are of paramount importance to control the life cycle of welded products.

The above-described aspects are driving factors to introduce a digitized welding production. In the context of this paper, the term “production” comprises design, fabrication, and service of a welded component or product, enabling a comprehensive information and life cycle control of welded products from cradle to grave. Although robotized welding has made the fabrication more efficient, one-off production is very typical in modern Western countries and challenges the economic profitability of welding production due to higher labor costs emerging from the operation and jig-preparation of robotized welding. Through the digitized welding production and digital twins, the one-off production can be accelerated enabling high-quality and cost-effective manufacturing of welded products.

Sensor technologies and software development have enabled the introduction of digitized sections in the welding production, and prior investigations have clearly indicated their capabilities to intensify the different stages (design [13, 14], manufacturing [15, 16], or service) of a welded product. Nevertheless, such development steps lead easily to a sub-optimization of different stages, while an optimized production demands the consideration of the whole production chain, from design to service. For instance, the design for manufacturing and assembly (DFMA) actions, in terms of welding, can significantly improve robot weldability or modularity of a product but can severely decrease the structural performance. In addition, it is worth mentioning that the prior contributions in welding production have principally contributed to the manufacturing stage, while information extracted from the design and service stages are increasingly important when taking steps towards a digitized product life cycle. The successful digitization of production requires multidisciplinary skills and collaboration between experts from design, welding, material, process control, sensors, and information technology.

The aim of the present paper is to demonstrate a concept of comprehensive digitized production, including design, fabrication, and end-use stages. For each stage, the main characteristics, related to a digitized version, are introduced and explained. Furthermore, the paper presents analytical models for an optimal material selection, together with the exemplifying demonstrations, as well as methods to account for service data in the design stage. Section 2 presents a general overview of the concept of digitized welding production, and compares it to conventional production chains with and without digitized features. The general overview is followed by the contribution to each stage—design, fabrication, and end-user—by demonstrating their role and summarizing their key characteristics in the digitized welding production. As the objective of this study is to present a conceptual

model for the digitized welding, no quantitative measures or actions in case-specific contexts are taken to evaluate the significance of the proposed model. However, the qualitative differences between the conventional and digitized welding production are demonstrated in Section 6.

2 Digitized welding production—general overview

The concept of digitized welding production is established on the basis of a normal life cycle of welded products—from the product design to, eventually, the recycling of material. Consequently, the digitized production comprises design, fabrication, and service of the structure. Figure 1 summarizes the key steps taken during the design, fabrication, and service of welded products, and exemplifies the available tools at different stages. The tools are widely utilized in a conventional process but, however, through a comprehensive digital twin, including both physical representation and design data of a welded product.

The main difference between the digitized production and conventional production is that the design of fabrication is a substantial part of the product design (see also Section 3 that describes these aspects more comprehensively). For instance, a common approach is that structural designers and/or analysts specify the geometrical shape and material properties, while welding coordinators and operators are responsible for determining welding parameters and conducting practical implementation. With a digitized fabrication with welding robots, the design of fabrication can be incorporated in the design phase. In addition, the active role of digital twins is an essential part of digitized welding production. Using digital twins, the technical documentation, and design and fabrication specifications can be formed and handled through the product life cycle and, thus, minimizing the workload associated with the communication, management, and acquisition of information.

Digitized production consists of design, fabrication, and service of the structure as illustrated in Fig. 2.

3 Design

Design consists of material selection, structural design, and the design of fabrication. Structural design starts with optimal material selection. Therefore, the designer must have all the potential material options available with the essential material data in digitized form, which includes the mechanical properties and additional information about other potential requirements (resistance to wear, weather, corrosion, subzero temperatures, etc.). All the material information concerning each potential fabrication process is included, such as cold-forming limitations (r/t ratios) for different rolling orientations

Fig. 1 Life cycle of a welded product: **(a)** conventional process flow, **(b)** tools that can be applied at different stages, and **(c)** digitized production

of plates. Welding plays an important role in manufacturing and so the weldability (e.g., CEV and Pc parameters, and CCT diagrams) must be considered during design.

3.1 Loading

In many applications, the structures are exposed to single high static loading peaks and fluctuating loading during the service history, as illustrated in Fig. 3.

The minimum yield strength f_y for the structure is then:

$$f_y > \gamma_F \gamma_{M0} \gamma_f F_{\max} \sqrt[m]{j \sum_{\Delta F_i = \Delta F_{th}}^{\Delta F_{\max}} \Delta F_i^m n_i} \text{FAT}_{\text{red}} \quad (1)$$

where

γ_F = partial safety factor for external load F (1.5)
 γ_{M0} = partial safety factor for yielding of material (1.0 or 1.1)

γ_f = partial safety factor for fatigue (1.0...1.35)
 $F_{\max}$ = maximum value of the loading (force, moment, etc.)
 ΔF_i = effective range of the loading
 ΔF_{th} = minimum (threshold) value for an effective range of the loading
 $\Delta F_{\max}$ = maximum value for an effective range of the loading
 n_i = number of cycles during the reference period
 j = number of reference periods during the total life (N_f) of the joint or structure ($= N_f / N_{\text{ref}}$)
 FAT_{red} = reduced fatigue class of the structure, including local (effects of thickness, local boundary, etc.) and the potentially improved quality.

It is important to note, that Eq. (1) obtains only the minimum for optimal strength level. However, the choice for higher strength steel can still be argued, e.g., by saving fuel, increasing capacity, or decreasing emissions in service of the device. Efforts to enhance FAT_{red} class are reasonable if a high-strength steel is used. In digitized

Fig. 2 Digitized production

Fig. 3 Typical loading history of a welded structure

design, these kinds of calculation tools are available to ease the material choice.

3.2 Throat thickness

Other parts of the design tools will deal with the design of throat thicknesses for different applications, including adjustment of the optimal cooling rate ($t_{8/5}$) by control of heat input (Q) and also the static strength design of fillet welds according to EC3 [17, 18] or more purposeful eccentric fillet welds, as discussed in [6]. The throat thickness of symmetric fillet weld defines the Q and thus, also fits the $t_{8/5}$, which can be roughly estimated by means of following Eqs. (2) [6] and (3) or (4) [19, 20].

$$Q = k \frac{UI}{v} \approx \xi a^2 \quad (2)$$

$$t_{8/5,2D} = (4300 - 4.3 \cdot T_0) \cdot 10^5 \cdot \frac{Q^2}{t^2} \cdot \left[\left(\frac{1}{500 - T_0} \right)^2 - \left(\frac{1}{800 - T_0} \right)^2 \right] \cdot F_2 \quad (3)$$

$$t_{8/5,3D} = (6700 - 5 \cdot T_0) \cdot Q^2 \cdot \left(\frac{1}{500 - T_0} - \frac{1}{800 - T_0} \right) \cdot F_3 \quad (4)$$

where

Q = heat input [kJ/mm]

- k = thermal efficiency of the process [-]
 U = arc voltage [V]
 I = welding current [A]
 v = travel speed [mm/s]
 ζ = material coefficient [kJ/mm³]
 a = throat thickness [mm]
 t = plate thickness [mm]
 T_0 = preheat or material temperature prior to welding [°C]
 F_2 = shape factor for 2D case [-]
 F_3 = shape factor for 3D case [-]

3.3 Digitized design

The digitized design toolkit will include all the calculation procedures. On the basis of the $t_{8/5}$ cooling time and CCT diagram, the local hardness and microstructure of the critical zones next to the fusion line can be estimated. In addition, the effect of heat-input-induced material softening on the static strength capacity must be considered, particularly in the case of ultra-high-strength steels [21].

The mainframe of the design consists of a conventional CAD-FEA-CAD-procedure (Fig. 4). The preliminary design is analyzed by a finite element analysis (FEA) and then the improved (final) construction is created and the digitized information is forwarded to guide the fabrication processes.

There can be several sub-loops inside this mainframe. One is the previously mentioned throat thickness design and the other is fatigue strength design, which plays an important role in the design of structures for demanding applications exposed to fluctuating loads. The FEA obtains stress concentrations on at least the structural stress level. In recent years, the computational resources have greatly increased and many commercial FEA pre-processors are also capable of automatic meshing of complex welded details. Nevertheless,

the requirement for short design times and potential design sub-loops claim the minimization of the complexity of FEA. Consequently, structural analysis using a hot spot (HS) stress model either with plate elements or, if possible, with solid elements provides an efficient approach. In many cases, such as in butt-welded joints and transverse fillet welded load-carrying or non-load-carrying attachments, the 3D geometry can be simplified to a 2D plane strain element model and the structural stress components $\Delta\sigma_{hs} = \Delta\sigma_m + \Delta\sigma_b$, obtained using 3D structural analysis, can be used as a basis of load conditions.

The digitized toolkit with the XX-FAT library (Fig. 5) includes the most typical welded joints. The designer or strength analyst can analyze the critical details using different fatigue strength assessment approaches, i.e., HS stress approach [22], effective notch stress (ENS) concept [23], linear elastic fracture mechanics (LEFM) [24], and the 4R method [25], by means of the predefined stress concentration factors (SCFs, $K_{t,m}$, and $K_{t,b}$) or stress intensity factors (SIFs, $\Delta K(a)$). The designed or assumed detail, or measured geometry of an existing structure are provided with the load condition (mean stress level σ_m and stress range $\Delta\sigma$ in terms of structural stress) and material properties (elastic modulus E , yield strength f_y , ultimate strength R_m). The mean stress level of loading is needed since the mean stress level correction is embedded in the 4R method. Different approaches can be employed to critically estimate the effect of different quality parameters on the fatigue strength capacity, such as weld toe radius and initial crack size. Using such a toolkit, a designer can quickly and cost-efficiently conduct a sensitivity analysis for the designed or measured parameters.

It must be considered that, in the case of LEFM, the simplification from 3D geometry to 2D plane strain geometry does not necessarily describe the 3D crack shape evolution

Fig. 4 Mainframe of the design of welded structures

Fig. 5 Principles and XX-FAT user interface for fatigue analysis using a joint library for different structural details, and predefined SCFs, and LEFM analyses

in a correct way. However, in terms of total fatigue life, the short crack propagation plays the most important role and, when LEFM is employed in fatigue assessment, the 2D models can be efficiently applied.

In order to utilize the increased structural performance of constructions made of high- or ultra-high-strength steels and having improved geometrical quality and compressive residual stresses (e.g., obtained by conducting high-frequency mechanical impact (HFMI) treatment), the 4R method is an efficient approach for calculating the improved fatigue strength capacity. The 4R method is applicable for welded joints and cut edges and the details can be seen in

refs [26–29], and showed high accuracy particularly in the high-quality post-weld-treated details [30–32] failing from weld toe, as well as weld root failures [33]. The idea of the method is shown in Fig. 6, and the fatigue life $N_{f,4R}$ can be evaluated using Eq. (5).

$$N_{f,4R} = \left[\frac{\sqrt{1 - R_{\text{local}}}}{\gamma_f (K_{t,m} \Delta\sigma_m + K_{t,b} \Delta\sigma_b)} \right]^{m_{4R}} \cdot C_{4R} \quad (5)$$

where

$$R_{\text{local}} = \text{local stress ratio} = \sigma_{\min} / \sigma_{\max}$$

Fig. 6 In the 4R method, a linear-elastic stress range is modified to elastic-plastic behavior by means of the Ramberg-Osgood and Bauschinger's kinematic hardening material models [34] and residual stresses

- $\sigma_{\max}$ = maximum elastic-plastic stress at the critical point of joint Fig. 6
 $\sigma_{\min}$ = minimum elastic-plastic stress at the critical point of joint Fig. 6
 γ_f = partial safety factor for fatigue
 $K_{t,m}$ = notch SCF for membrane stress
 $K_{t,b}$ = notch SCF for bending stress
 $\Delta\sigma_m$ = structural stress range, membrane component
 $\Delta\sigma_b$ = structural stress range, bending component
 m_{4R} = slope of the Master Curve Fig. 6
 C_{4R} = fatigue capacity of the 4R Master Curve ($C_{4R, \text{char}} = 10^{20.83}$ and $C_{4R, \text{mean}} = 10^{21.59}$)

Because the mathematical formulation in the 4R approach is quite complicated, the method needs a numerical tool in order to be applicable for engineering practices. Although the theoretical background can be very complicated, all the 4R parameters can be obtained using the normal engineering tools [25]. Thus, the 4R method will be an essential part of the digitized toolkit. The method can also be used to evaluate the sensible use of high-strength steel materials as illustrated in Fig. 7.

4 Fabrication

In digitized production, the design of fabrication means that all the information needed to guide the fabrication processes must be included in the design data. Thus, each fabrication stage must be designed in a more detailed way when compared to conventional manual or semi-manual manufacturing. Those stages can vary according to the product but an illustrative case is seen in Fig. 8. In that particular case, the design of production includes cutting, cold forming, drilling, turning, and welding with its sub-stages, such as tack welding and welding and post treatment.

4.1 Manufacturing stages and processes

The optimal fabrication parameters for each process are available from material data bank (e.g., r/t ratio in cold forming) or they will be calculated by means of a design toolkit (throat thickness and degree of penetration). Similar to the well-known welding procedure specification (WPS), the essential parameters of other workshop operations, such as cutting (CuPS), cold forming (CFPS), turning (TPS),

Fig. 7 Comparison S-N-curves defined by the 4R method and conventional ENS approach following the IIW design guideline [35] for the S700 and S1100 steel grades with distinguishing residual stresses

Fig. 8 An example about the idea of fabrication design

drilling (DPS), milling (MPS), and casting (CaPS), are also defined and documented. In addition, inspection procedure specification (IPS) is applied for quality assurance purposes and to ensure the required quality of the structure. Naturally, all the information is in digitized form and the fabrication data can thus be downloaded to the manufacturing machines without any manual work or tacit knowledge. Tack welding (TWPS) will be avoided as much as possible by means of digitized jigs and service robots, which will carry out the parts and components so they are in their correct place and position just on time. All the necessary information for each process stage can be read from cloud, e.g., via QR-code. For robotic welding, the fabrication process is seen in Fig. 9.

4.2 Quality management

In order to achieve high quality and productivity in robot welding, sensors and measurements are required to adapt in the system because they enable precise control and adaptivity for the welding of unideal real-world parts and structures. In other words, welding parameters, positions, paths, etc. programmed and simulated based on the ideal numerical design model can be adjusted to actual structure by means of sensor and measurement data. In addition, real-time data gathering enables instant feedback control and adaptivity of the welding process. This will ensure to meet both the quality and productivity requirements in question. Penttilä

[36] has introduced an intelligent welding system, which is comprised of the welding process, sensor technology, simulation, control algorithm, data management, and IoT system. Depending on the needs and the requirements of the welding and quality measures, various sensor technologies can be utilized during welding. Sensing and measuring can be conducted before, during, and/or after welding, e.g., by means of laser triangulation scanning [37], which can enable jigless multi-robot welding applications [38]. The quality and adaptivity data can also be gathered with other optical devices and systems (active or passive vision) [39], thermographic cameras, as well as acoustic emission, magnetic field, and radiographic sensors. In addition, welding parameters (current, voltage, wire feed speed, shielding gas flow, etc.) from the welding power source [40] and operating data from welding robot are also important information. The most common sensors utilized during welding are acoustic sensors that can be applied to evaluate the stability of the process, thermal cameras to measure temperature distribution and cooling time, and laser triangulation sensors to evaluate the dimensions of the seam. Employing an artificial neural network (ANN), the welding system gains its intelligence by combining the input (welding conditions) and output data (welding process parameters) of the welding process. The intelligent system can be trained with the different input-output combinations, by categorizing the outcome of welding quality output in the training phase. Hence, the parameter

Fig. 9 Digitized robotic welding system

control window can be created in which the quality remains consistent in varying welding conditions. Thus, the consistent quality of the weldment is ensured by means of real-time feedback control of welding parameters, which is based on the measurement of welding conditions during welding.

One solution for quality management of welding and weldments is the Wintaria system [41], which can measure and analyze the geometrical properties of the produced weld joint either in the course of welding or afterwards. The system, which includes laser sensor and

software, is based on analyses of real-time laser scanning data from welded joint. In terms of quality and fatigue durability of welded structures and products, essential factors are weld toe radius and flank angle (Fig. 10), which cause local notch effect on the weld joint that can be defined applying a FEA [42], ANN calculations [43, 44], or analytical approaches. For example, the notch stress concentration factor of a butt weld subjected to tensile loading can be calculated based on Anthes' Eq. (6) [45].

Fig. 10 Fillet weld profile at certain point and statistical distribution of (a) weld toe radius and (b) flank angle in user interface of the Wintaria software

$$K_t = 1 + 0.728 \left(\frac{t}{r} \right)^{0.382} (\sin \beta)^{0.932} \quad (6)$$

where

t = plate thickness
 r = weld toe radius
 β = flank angle

The stress concentration factor (K_t) alone will describe the produced quality of a weldment but in addition, knowing the strength of the material (R_m), e.g., assessed from hardness measurements by means of Pavlina's correlation equations [46], defining the residual stresses (σ_{res}) with either measurements or simulations, using the FEA to determine the notch stress range ($\Delta\sigma_k$) caused by external loading and specifying its stress ratio (R) the fatigue life of a welded detail in question can be calculated applying the 4R method [27, 28]. Thus, this type of digital quality assurance approach enables to generate fatigue strength estimations from different locations of the structure simultaneously during the welding process. In addition to fatigue life analyses,

the digital quality data achieved from sensors and measurements can be utilized to control the adaptive robot welding cells and systems.

5 End-user and service

LUT is developing a novel real-time fatigue monitoring system that utilizes the 4R method introduced in the above-mentioned design tool. The monitoring system evaluates the remaining fatigue life of a construction, using given survival probability and confidential levels and assuming that the loading will continuously be repeating. The system also reports the current damage rate of loading. Both results are visualized for the operator and they can also be read remotely. The system is illustrated in Fig. 11.

Because the fabrication is digitized and the quality is fixed in design, the fatigue life of the critical joint of the structure should be matched with the calculated result (higher accuracy with respect to conventional methods), assuming the loading is known beforehand. However, this is the weakest link in the evaluation. The real-time monitoring of the service load is not

Fig. 11 Description of a real-time control system of the fatigue rate and accumulation (patented ReFaMo system [47])

a new idea. Nevertheless, it plays a new role in the digitized production because it will give feedback for design, fabrication, and material development. All those processes in production chain can exploit the fatigue monitoring and develop the quality, which is easier due to digitized documentation. The design will then receive information regarding the real loading of the structure, which is important for the future design of new products. The loading of a construction can be quite distinguishing in different service environments, while this information is also important for design. Because the service load can be blocked according to working periods, the designer can create new loading combinations by calculating new equivalent loadings σ_{eq} based on the blocks, using Eq. (7).

$$\Delta\sigma_{eq} = \sqrt[m]{\frac{\sum_i \kappa_i \Delta\sigma_{eq,i}^m}{\sum_i \kappa_i}} \quad (7)$$

where

κ_i = weight factor for each loading block
 $\Delta\sigma_{eq,i}$ = equivalent stress range for each loading block
 m = slope parameter of S-N curve

Due to the visualization of current damage rates, the user of the device or operator of the process can see the impact of their working manners and learn more efficient ways to use the device without causing it extra damage. By applying an ANN, the device can be applied to optimizing the efficiency-to-damage ratio during service. Due to the capability to being able to evaluate the rest of fatigue life, the service group can schedule the necessary maintenance or repairs in time avoiding costly interruption in work and production. The owner can optimize for recycling when it is time, as well as for new investment and for when the repair still makes sense. Furthermore, in the case of a change in ownership, the load history and residual fatigue capacity becomes an important issue. Digitized production obtains valuable information regarding material development from design (will the properties be adequate theoretically), fabrication (how the material behaves under different fabrication processes), and service (how the structure behaves in different loading conditions and environments). Thus, the material can be recycled indefinitely, constantly producing new information for the optimization of digitized production.

6 Discussion

Nowadays, a wide variety of steel grades are available for different industry fields, of which products and applications demand various properties from the material used. However,

the properties of welded joints determine the performance of a component, structure, or final product usually more than the properties of pure base material [48]. Thus, after appropriate material selection, the structure must be designed and fabricated properly. The main challenge is to retain the good properties of the base material throughout the whole production chain all the way to the functional properties of the final product. In order to achieve this, the high quality of working must be carried out in each level of the production chain. In addition to general standards and guidelines, for the quality assurance of welding and welded joints [49–52], extensive concepts for analyzing and governing the quality of design and fabrication of welded steel structures have also been introduced [1, 53–55]. These can be utilized, for example, when producing welded structures from high- and ultra-high-strength steels, of which use has increased during past decades in the engineering industry due to their potential in terms of payload capacity, structural durability [56, 57], energy efficiency, emission control, life cycle management, and recycling [58, 59]. However, the application of high-strength steels causes often restrictions on the rules for design [18, 60], narrower parameter windows for fabrication (e.g., welding) [6, 61–63], and more specific precepts for inspection, due to the basic fracture mechanics law where the critical crack size decreases when the strength of the material increases [64], compared to the corresponding mild steel structures. Consequently, the management of the production chain by means of digitalization is emphasized in these types of demanding welded structural applications.

Compared to the conventional production process, the advantage of using digitalization in the production of welded structures can be gained in each level of the production chain, as shown in Table 1. Among other things, minimizing the risk of human errors is just a single benefit but the most important matter is to enhance the production process as well as control and reduce the waste time and material, along with duds. In addition to forward moving data in the production chain, the digital information flow to backwards enables the recognition of the critical parts of the product in terms of both fabrication and service aspects, and this knowledge can thus be utilized to develop the design phase. Regarding this, it is important that the data from fabrication and service is available and shared to designers; i.e., open communication between different operators is essential in order to achieve the maximum effectiveness of the system. The question about the ownership, share, and protection of the data available from the system as feedback information will be an important topic in practice in future studies. Particularly in short-run productions, the bottleneck of the production chain will shift from workshop fabrication to design phase (Fig. 12), whereupon efficient operations and procedures are needed in order to solve the problem. One solution

Table 1 Comparison between conventional and digitized production of welded structures

Production chain phase	Theme	Conventional process	Digitized process	Comment
Material	Design	Normal/standard	Improved	More information available
Design	Input data	Nominal values	More accurate	Simulated or measured information available
Fabrication	Efficiency	Based on human skills and computational resources	Improved	Ease time-consuming search of data
	Role	Minor or equal compared to other production phases	Increased	More detailed information
	Quality	Mainly based on human factors	More detailed but no guarantees for better quality	Risk of human errors decreases
	Costs	Normal/standard	Increased	Comprises detailed fabrication plan
	Input data	Nominal values or no data	More accurate and detailed	Generated in conjunction with structural design
	Efficiency	Normal/standard	Improved	Optimal parameters and more detailed data as well as automation and adaptivity
	Lead time	Normal/standard	Shortened	Just-in-time principle
	Quality	Mainly based on human factors	Increased	Risk of human errors, along with waste and duds, decreases
	Costs	Normal/standard or increased due to waste and repair of duds	Decreased	Optimized material flow
	Control	Mainly based on feedbacks from end-users	More accurate	Measured information available
Service	Warranty	Normal/standard	Improved	Number of reclamations decreases
	Maintenance	Not included or normal/standard	More efficient	Optimized maintenance intervals
	Repair	Not included or normal/standard	Less and more focused	More detailed information
Re-	Reuse	Not included or normal/standard	Optimized	More accurate life cycle estimations
	Recycling	Not included or normal/standard	Improved	Specific recycling of materials, components, structures, and products

Fig. 12 Bottleneck in production chain, especially in short-run productions, can be broken by means of digitalization

is that instead of having the traditional separation between design and fabrication aspects, both the structural design and the design of fabrication are merged and thus processed and governed in the design phase. As a consequence, the digitalization makes possible to achieve equal lead time in production regardless of the number of pieces. In terms of service, the number of reclamations from the end-users decreases by means of digitalization. The main reason is the increased quality of both design and fabrication and the real-time fatigue monitoring system afford also detailed and accurate information for the possible maintenance and repair

procedures. Furthermore, the improved life cycle estimations enhance the reuse and recycling of the materials, components, structures, and finally the whole products.

Digitized production offers huge potential, allowing for the development of the whole production chain on a higher level in terms of quality and cost-efficiency. The paper deals with a new concept to establish digitized production system for the welded structures in demanding applications. Although the presented concept is generic, a platform or interface which enables the embedded software to automatically communicate with each other still

needs huge efforts, and is highly dependent on the environment of the application. In many practical applications, the movement to direction happens in a certain critical area, e.g., in welding. However, the most pressure is on design because all the digitized information will be created there. In high-income countries, like vast majority of the Western and Northern European examples, there are several reasons to implement this direction step by step and separate parts of the concept presented in this paper are already utilized in welding production industry, e.g., in some engineering/design offices and welding workshops. However, achieving completely digitized production requires a great deal of research and engineering work. In order to implement the whole digitalization concept into practice, it would require complete production chain and network, including material and intermediate product manufacturing, design, fabrication, service, and recycling of the end product, to be harnessed into this and in addition, it could act as a platform for further researches in the field of digitized welding production. It is a big challenge to be met but we are on the way to that goal.

7 Conclusions

Based on the concepts studies and analyses presented in this research, the following conclusions can be drawn:

- Appropriate digitized production takes into account the whole process chain including material selection, structural design, design of fabrication, fabrication processes and operations, inspection procedures, and monitoring the service of the final product.
- Instead of applying traditional machine learning, etc., concepts, it is also possible to develop and create a digitized production system based on data processing, which utilizes well-known physical principles and strength theories in connection with design, fabrication, and service of welded structures.
- Increased automation and digitalization in fabrication, especially in welding applications, set demands and pressures for developing and modernizing other sections of production, as well.
- Regarding the production chain, the design phase is the most crucial field because the digitized information and data is generated there and thus, it governs the following phases, such as fabrication and inspection.
- In the future, managing the digital production process is important for structures made of high- and ultra-high-strength steels where achieving high level of quality and short lead times generates a competitive advantage in the market.

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