THE TONNAGE-FLOW

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ABSTRACT

In steel fabrication and erection, the production flow is measured by counting the amount of fabricated and erected tons. This leads to several questions: is this indicator sufficient to visualize the real productivity? Are there better metrics to display process performance? Thirdly, how can lean methods like pull, Kanban, ConWIP and SMED improve these processes? A study of steel fabricators in Germany and Chile revealed that the only KPI today is the global metric of [hours/ton] related to the finished products. The lack of performance metrics, high process variability and individual production justifies the first research question concerning whether there are common patterns behind all steel-fabrication processes. Further questions involve finding the right metrics and determining which lean-methods could be best applied at certain work-stations to optimize the whole production flow. Data is measured in detail considering the whole steel-fabrication process including the erection of the building on site. This paper provides an exemplary in-depth exploration of the cycle times and process variability of the work-stations conducting “fitting-welding” operations. The application of PULL through Kanban and CONWIP as well as takt-time control and SMED is discussed. A three level KPI-concept is elaborated, to support pull in the whole supply chain. Finally the study provides a basis for simulating the steel-fabrication and erection process as tonnage flows by continuous simulation (HECRAS) or the one-piece concept of DES-Simulation (SPS).

KEY WORDS

Steel-fabrication process, Production metrics, Process variability, Standardisation, Product complexity, Continuous- and discrete event simulation

INTRODUCTION

Steel is being used in most of the construction projects because of the flexibility, speed of erection and the economic benefits that it provides for the designers and the contractors (AISC 1998). Structural Steel is mostly fabricated in controlled shop environments off-site, for better precision and accurate detailing. The different parts are then grouped together as modules at steel-fabricators and then assembled on the construction site (Hofacker & Ghandi 2009).

Steel fabricators originate from small handcraft enterprises that expanded to larger companies over the years, residing in between the make-to-order-construction industry and large-series of manufacturing industry. Hence, steel fabrication is a stationary project based industry with low repetitiveness in production and a diverse

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range of products. Figure 1 illustrates the supply-chain of steel products and the consideration frame of this analysis.

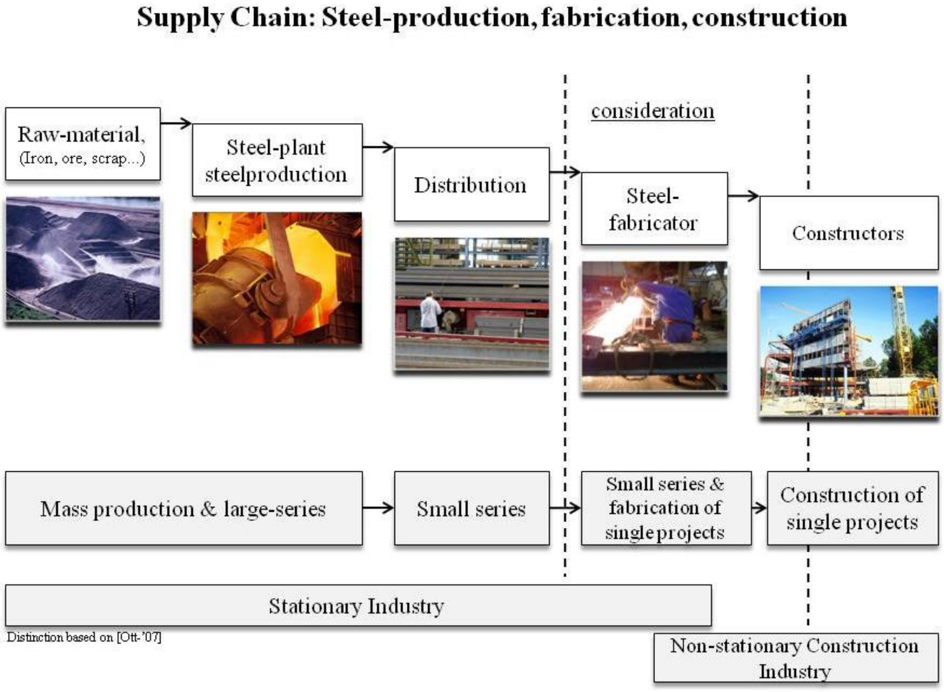


Figure 1, Steel-supply-chain: production, fabrication and construction

Most steel fabrication shops leave the planning and scheduling of production totally to the personal experience of production managers. The only supporting tools used are Production-Planning-Systems (PPS) to feed the CNC-cutting machines with the available product drawings and to get some feedback about the current status of the shop floor (Abourizk, Song & Wang 2005). These tools offer very limited opportunities to visualize process flow variability and to evaluate different production management scenarios. Moreover, these tools do not show waste or non-value adding time. Hence they are inadequate to manage the production flow, to detect potential to optimize the performance of production.

Structural Steel Fabrication is a process where a steel piece, e.g., a heavy plate or a beam, is cleaned and then detailed (i.e. cut, drilled, etc.) as defined by a fabrication drawing. The fabrication drawing provides all details about the dimensions of a component to be fabricated, and its location to be fitted together with other subcomponents. After the detailing process, different components are manually fitted together with pointed welding-tacks, again as given in the drawings. Then the product is manually or semi-automatically welded for acquiring the required strength. Afterwards it is cleaned to provide a smooth surface, painted for surface protection and then shipped to the construction site for erection (Hofacker, Ghandi 2009). Figure 2 shows the typical main production process in Steel Fabrication. In a typical steel fabrication work-in-process material (WIP) exists between all work stations.

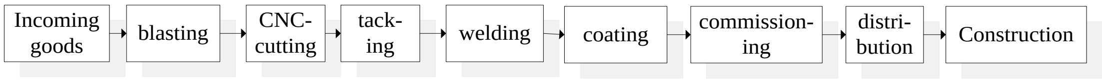


Figure 2: Main production process of steel-fabrication

Production management of steel-fabrication processes remains with two controversial questions:

1. Is steel-fabrication to be considered as craftmanship or as a fabrication industry of single- and small series production?

The first perspective relates to the idea of production as something like art. The second perspective focuses on potentials of standardisation and modularisation. Interviews showed, that this question is not clearly responded in any of the investigated case-studies (Hofacker, 2008).

2. What is the right production figure to look at– tonnage or number of pieces?

Both figures do not fully reflect production reality in regards of finding an indicator that illustrates the real effort of the production process. There are reasons to follow the tonnage-flow idea as well as the single parts perspective. In a steel project, all parts are counted in production lists (bill of material), containing the quantity and corresponding number of parts with their respective weights, in a typical range from 0,1 kg to 20 tons per component.

Due to this contradiction, both figures [*time per number of processed part*] and [*time per tonnage of product being processed at the work station*] are tracked in this research on the whole supply chain. In addition the study revealed, that other KPIs are needed at certain work-stations (e.g. at fitting and welding stations).

HYPOTHESIS AND RESEARCH METHOD

The hypothesis consists of three main investigation points:

1. The single used performance metric [hour/tonnage] is not sufficient to improve the production flow of steel-fabricators, however it allows the application of continuous flow-simulation, which can highlight effects of bottlenecks, like in hydraulic engineering.
2. There are common patterns behind all steel-fabrication processes and the production is currently in push-mode.
3. KPIs and measurements can help to highlight process variability and evoke change towards a pull-system.

Evidence for the hypothesis is proved by a research method that combines case studies with literature research. A series of four pre-studies is conducted, including production site investigations and interviews over several production days at each company to understand the current enterprise situation. Two steel fabricators are then selected to conduct detailed measurements based on Rother’s approach (Rother 2009). Hereby, the whole value chain is considered, starting from incoming material (beams), cleaning, cutting, welding etc… until the erection on site. Transport time, waiting time, processing time and stocks are measured at each point over several cycles. The data is afterwards presented to the employees of the respective company, enabling discussion on the effects and consequences of seeing variability in the process, highlighting some system constraints and waste.

In a third step, the measured data is used to simulate effects on the throughput time by incorporating different lean methods in the model (Kanban, Conwip, takt-time control and SMED). Simulative investigations are not yet finished and two different simulation streams are followed. Firstly, a model based on continuous simulation is developed using an open-source software (HECRAS). This is typically used in hydrualic-engineering, which is now applied to steel-fabrication, and therefore called the tonnage flow model. Secondly, a model is under development to simulate the flow of single pieces, based on discrete-event-simulation (DES, based on the SPS software).

KEY PERFORMANCE INDICATORS IN STEEL-FABRICATION PROCESSES

Steel-fabricators estimate the price for each project for constructors by the amount of tons of steel that are used e.g. for building a car-park. Therefore the tonnage metric is kept until today at all visited companies. However, once looking into the detailed production process at work stations, it is evident that the cost in terms of time effort per ton is highly variable [h/ton]. For instance the time per ton for cutting and welding many small detailed parts together is higher than handling two large beams.

Commonly used Production-Planning Systems (PPS) assign operators' working hours to the order number of the current project. This enables to calculate at the very end an average number of completed working-hours for a completed project. This data is used for financial controlling. Yet it suggests that production is correctly measured and fully under control, - which is not the case.

The KPI of [hours/ton] does not enable application of the flow-model of Koskela (1992,2000), distinguishing between time units related to activities of transport, wait, inspection and processing. Simplified said, the current indicator is the classical case of the transformation model, considering raw-material as input, the steel-fabrication process as one black-box of production and the steel modules erected at the construction site as the output.

How is it possible to get the consciousness of flow into this process? Following the request of "Go and See" (Rother 2009), it was chosen first to measure the process in detail, due to the lack of existing data. Figure 3 illustrates the detailed measurements taken at one of the steel fabricators including their construction sites.

The researcher spends one day for data collection at each process step. In parallel, PPS-data of 10 finished steel-construction projects is observed, to analyze possible correlations between the number of designed parts and the work-load for the project. Three different patterns are detected as an outcome from the measurements and analysis. The first pattern illustrates process variability and the inadequacy of the tonnage-KPI. The second pattern reveals the fact that all steel fabricators are in a push-production mode, initiated by the CNC-cutting machines. The third pattern illustrates the correlation between project complexity, number of different parts and the bargain between optimizing design and material costs versus production costs, based on the analysis of 10 projects. In this paper, only the first pattern is described in further detail, due to the paper size restriction.

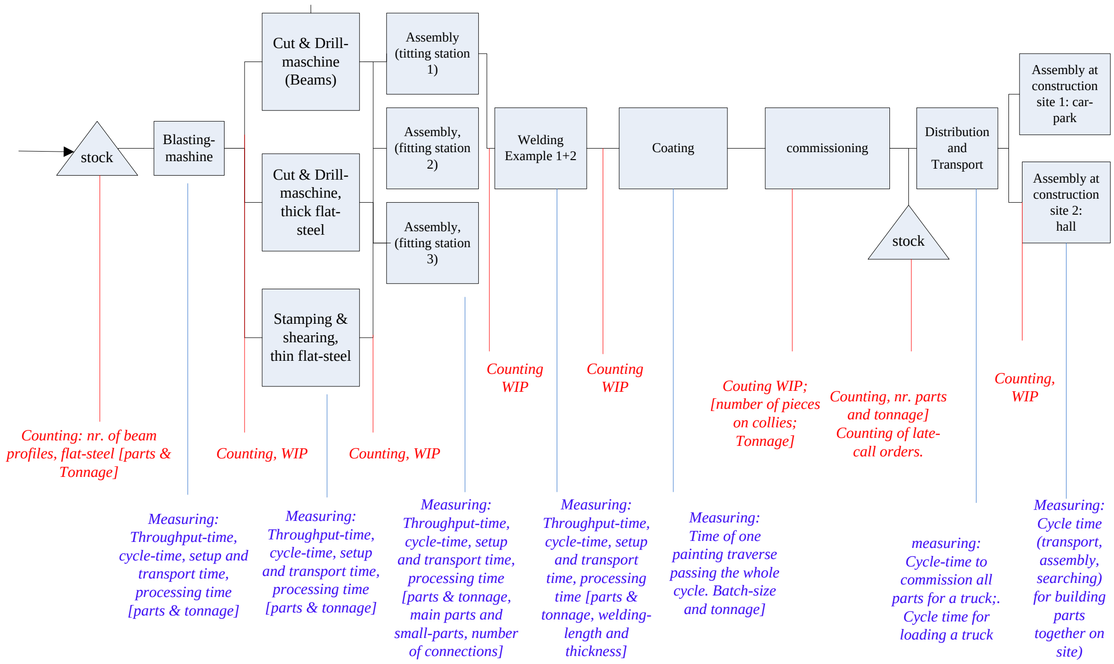


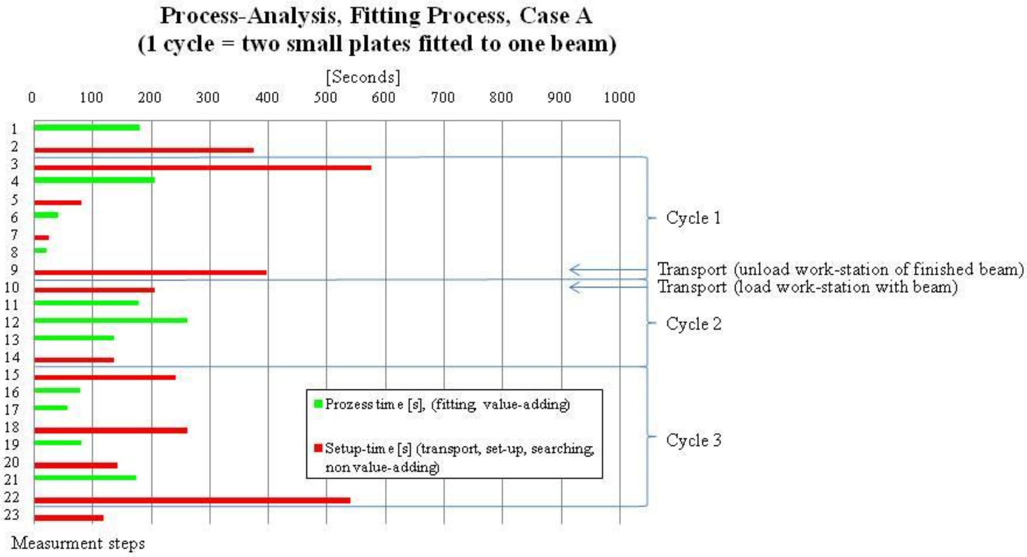
Figure 3. Process measurements (transport, waiting, processing, and inspection) and WIP over the whole steel-fabrication and construction elevation process (author).

Pattern 1: Process-variability and inadequacy of the tonnage-KPI

Two detailed process examples of the fitting-work-stations are shown in the following. This type of work-station is manual. The activities consist of loading the workplace with one or two beams (main components) and scratching the precise location where to tack several small parts (sub-components) to the main component. One cycle is finished, once the beam is unloaded from the work-station by crane to the following welding place, and the next beam is taken again. Value adding time (processing) is the time spent for tacking parts together. Waste or non-value-adding activities are all the activities apart from processing, thus set-up time, transportation, waiting or searching.

The observation time illustrated in case A (Figure 4) is 1.6 hours, corresponding to the finishing of four main-components. Two to three sub-components are fitted to each main component. Figure 4 shows the measurement steps and time of each value-adding activity (bright) and non-value adding set-up or transport time (dark). The variability and cycle time is clearly visible. Important is also the high amount of transport time. Summing up the single time measurements leads to 32% of VA and 69% NVA activities.

The number of incoming-outgoing parts and their respective tonnages are measured during the observation time (table in Figure 4). This enables to calculate throughput of tons and pieces as well as the number of connection points over time. WIP in form of tonnage and number of main-components before and after the work station is recorded. Documentation over all workstations provides the possibility to calculate and simulate the whole production as a flowing process afterwards.



Observation time [seconds]	5841
Income: [nr. beams]	4
Income: [nr. small parts]	19
Outcome: [nr. finished parts]	4
Q, throughput [tonnage/hour]	0,804
Q throughput [nr.output parts/hour]	2,47
[Nr of connection points / hour]	15
WIP [tons of beams] before workstation	33,48
WIP [nr.beams] before workstation	108

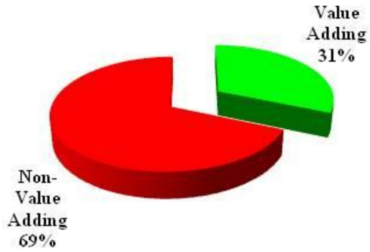
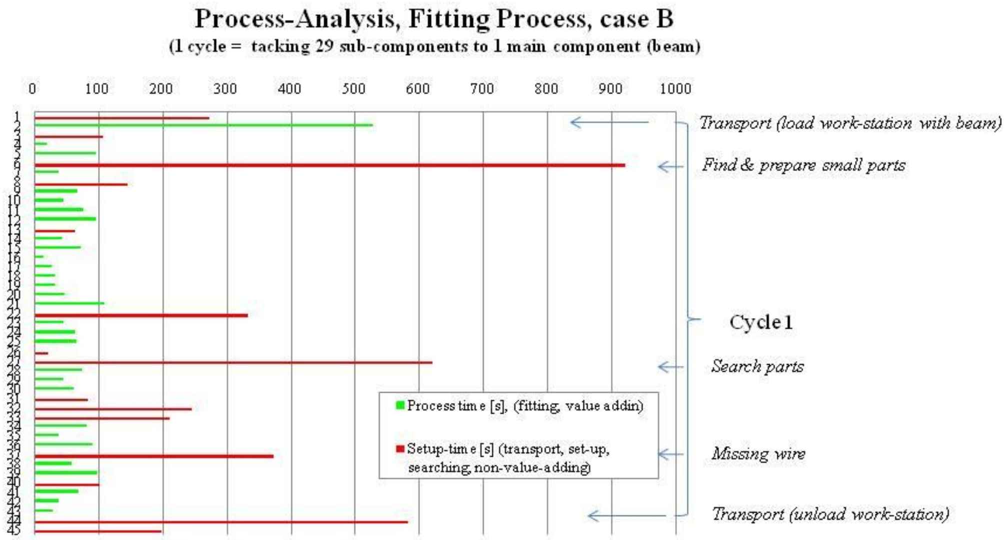


Figure 4. Process variability of the fitting process, measured data, case A

The PPS system tracks in this case merely the performance metric of 0,804 hours of working time per ton. The example in case B is the same type of working station, also managed by one operator with the same process of tacking small pieces to a beam. The single difference is the specification in the drawing. At this point 29 subcomponents are fitted to one beam. The observation time shown in Figure 5 is 1.7 hours.

In Figure 5, high variability of set-up times is still remaining. The value-adding ratio of 35% VA and 65% NVA also resembles the results of case A. According to the observation judgement of the researcher, both operators in case A and B worked equally well. However, the measured result in terms of throughput (tons/hour) in case B is only 0,329 tons/hour, representing less than half of the "productivity" compared to case A. Furthermore, only one cycle is completed within 1.7 hours, compared with 4 cycles in case A.

These numbers constitute that the h/t KPI is inadequate for this work station. As a result is found another metric to track the performance of the fitting stations, which fits to both cases: ***the Number of fitted connections per hour*** (15 in case A, 17 in case B). This metric also corresponds to the definition of the value-addition at the fitting station: "to fit two parts together as fast as possible, at the right place".



Observation time [seconds]	6280
Income: [nr. beams]	1
Income: [nr. small parts]	29
Outcome: [nr. finished parts]	1
Q, throughput [tonnage/hour]	0,329
Q throughput [nr.output parts/hour]	0,57
[Nr of connection points / hour]	17
WIP [tons of beams] before workstation	58,59
WIP [nr.beams] before workstation	189

Figure 5. Process variability of the fitting process, measured data, case B

Summarizing the two examples reveals the following pattern: the currently used metric [tonnage/hour] does not reflect the work-load of the fitting station. Process variability and set-up times are not visible with this indicator. The metric [Number of connections/hour] better reflects the real work load of this operation. Combining this metric with an error-tracking KPI enables to track the real value-creation at this work-station.

The two cases are chosen as an example of detailed process analysis, with the objective to understand and question the current way of metrics in production management. Fitting is considered as the core of steel fabrication and it is one of the most labour intensive processes. Several organisational units, information- and material flows come together at this station. The example of case A and B is regarded as one single piece of the whole steel-fabrication value-chain, keeping in mind to first understand and consider the whole process, before optimizing single work-stations (Koskela, 1992), (Santos, 1999), (Gehbauer, 2006). However, the same analysis is conducted in the complete study on all work stations, including the erection of modules at two construction sites.

HOLISTIC APPROACH OF LEAN-METHODS RELATED TO STEEL-FABRICATION

A holistic approach of lean-methods is defined, based on the beforehand detected three pattern (push-production, KPIs and design complexity). Process transparency is the precondition to successfully implement lean-methods like ConWIP, Kanban, SMED or others. Change and improvement cannot be seen without metrics that visualize the production process. The design prerequisites for a successful KPI system are based on multiple interviews with steel-fabricators.

One of the most requested criteria is simplicity: a performance indicator is to be as simple as possible, it should collect only value-adding information and be straightforward understandable and collectable. The purpose of a KPI-system is to control and improve the production flow. A three-level approach is suggested in the elaborated KPI-concept:

1. Controlling the whole production flow, according to pull-principles (Assembly-time-section (MOAB), as requested by the construction site).
2. Visualization and increase of the productivity (VA-time and effort) at each work station.
3. Visualization and reduction of mistakes (quality improvement).

Applied to the steel-fabrication process, an adequate metric-system focuses first on the target-production concept: Driving PULL into the whole system, thus ordering and supplying the right product when it is needed. In this case the steel-fabrication process is triggered by the assembly date at the construction site (MOAB). Critical success factor from the steel-fabricators side is the reliability of the due date delivery and from the construction side the actualization of the assembly date in case of changes. The MOAB resembles a type of takt-time for the whole steel-production process. A second focus in designing a metric system for visualizing production flows is the efficiency of each production-workstation. Once the takt-time and order sequence (MOAB) for production and delivery is clear at each work station, the target is to optimize the value-adding activity time by reducing set-up and NVA-operations. There will be more than solely one indicator for the second type of KPI level in steel fabrication. For the fitting stations the metric will be different than for cutting stations or the construction-assembly process. These secondary indicators enable to use supplementary capacity of freed non-value adding times for the improvement of the whole production system. The third-layer indicator tracks all mistakes at each work-station (time, quantity and quality), combined with root-cause analysis.

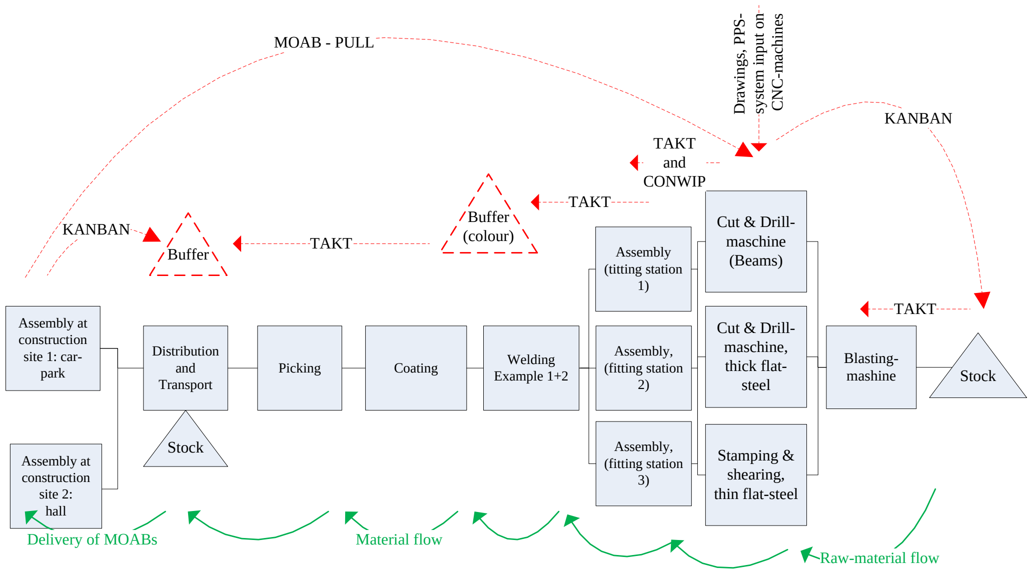
Following these requests, a KPI-system supports the production at the right time, when needed by the client (construction-assembly), improves productivity with a process-perspective. It provides freed set-up times for further system improvement, and improves the overall quality of products and process. Figure 6 illustrates a holistic model applying lean-methods and production-managment metrics on a steel-fabrication process.

A small buffer stock will remain between cutting machines and fitting stations, as the variability of the fitting stations remains high. However SMED can reduce the set-up times and the buffer beforehand can be operated with a CONWIP concept. CONWIP defines a maximum stock level (Peter, 2009), e.g. corresponding to the work load of one shift. This approach can significantly lower the current stocks and reduce searching and transport time.

The application of SMED methods at all work stations with high variances in set-up times will provide opportunities to optimize production and to smoothen the material flow. Shop-floor-management systems as used in the automotive industry or the Construction-Operation-Board (Hofacker, Hickethier 2009) are possibilities to track this data at regular meetings. The form can be similar to simplified Last-

Planner-Meetings (Ballard, 2000). The production control follows the requests from MOAB-dates, triggering the initiation of production orders at the cutting stations and afterwards being produced in a fixed sequence with takt-time. Design can contribute to optimize production costs by simplifying the structural drawings and using fewer parts per ton, or on the other hand to optimize the material-costs, depending on the higher outcome.

„Up-side-down“: holistic management model for the steel-fabrication-process in pull-mode



	Construction / Assembly	Distribution	Picking	Coating	Welding	Fitting	CNC-cutting	blasting	Incomming goods
1.level KPI: Pull-process control	*Initiate MOAB*	*KANBAN*	*Takt = MOAB*	*Takt = MOAB*	*Takt = MOAB*	*Takt = MOAB*	*Takt = MOAB*		*KANBAN*
2.level KPI: Operations performance	*[h/ correctly elevated ton] [PPC; MOAB]* call Buffer	*Time to finish loading of one truck completely*	*Time for picking all parts for one complete colly*	- color Buffer	*Welded area (length x thickess) per time & [h/t]*	*Number of connections per time & [h/t]* ConWIP Buffer	*Set-up time reduction; & [h/t]*	*Time to deliver KANBAN order*	*Time for unloading a truck*
3.level KPI: Quality improve-ment	*[nr. & type of error per project]*	*[nr. & type of error per truckload]*	*[nr. & type of error / missing parts per colli]*	*[nr. & type of error]* *SMED*	*[nr. & type of error]*	*[nr. & type of error]* *SMED*	*[nr. & type of error]* *SMED*	*SMED*	*[nr. & type of error]* *SMED*

MOAB = due date of assembly per section

Figure 6. holistic steel-fabrication production model, managed with a metric system including lean-methods (SMED, Kanban and CONWIP)

The conducted process measurements provide a perspective of a current steel-production system, illustrating its flow, set-up times, variances and intermediate stocks. Fitting all this information together into one large production map enables a net of tonnage flows as throughput Q[t/h] and a net of discrete events flows as Q[parts/h]. This provides a basis for examining the effects of applying lean-methods with two types of simulations (continuous and DES). However, even without dynamic simulation and based on static observations combined with these measurements analysis allowed to define such a holistic lean approach for the steel fabrication process, focusing on both, the "big picture" with detailed perspectives and continuous improvement. This result of the three-level KPI-system with the focus of pull-production in this supply chain was presented to the steel fabricator and is now in preparation to be implemented.

CONCLUSIONS AND OUTLOOK

The research based on six steel fabricators shows that the currently used performance metric of [hour/tonnage] in steel fabrication processes does not represent the real work effort e.g. at the fitting and welding stations. Additionally, it is inadequate to visualize process variances and a distinction of value-adding activities and set-up times. Three common patterns in steel-fabrication processes are detected in the study, of which the pattern of "process variability and performance metrics" is explained in detail. The small sample size limits the generalizability of the results, whereas the detailed data measurement over several cycle times of the whole supply chain (including site erection) is difficult for researchers to collect and unique. Previous existing time studies of steel construction at site erection focused on waste related to waiting time e.g. of non-working operators (Diekmann et al 2004). The focus of the prevailing research is solely based on the process, thus the material flow with its variances through the steel-fabrication and construction system.

A method is presented to develop lean-supporting KPIs for the steel fabrication process with an approach of three levels. Application of this method led to a holistic pull production management model. Hereby several lean methods like Kanban, SMED, CONWIP or takt-time are proposed to be included at certain points into the system. The study also forms the basis for consecutive investigations by simulating the effects of lean-methods on operations and the whole system throughput. Future work is required to enlarge the sample size, to further validate the holistic pull-KPI-model and to conduct further research, comparing results of dynamic simulation in the two modes of continuous simulation (tonnage-flow) and discrete event simulation (piece-flow).

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