The value of lean construction : a model of performance measurement for lean building projects

The Value of Lean Construction

A model of performance measurement for lean building projects

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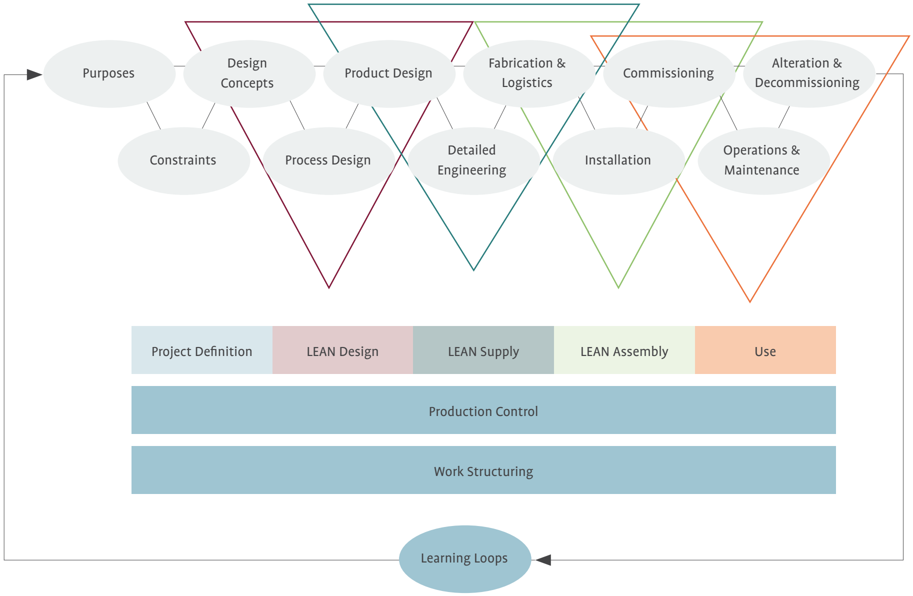

Figure 1-1 Lean Project Delivery System (Ballard and Tommelein, 2012).

1. Introduction

1.1 General

Despite the new management methods in the construction industry, not enough progress has been made in terms of efficiency. Even after approximately 15 years, there has been minimal use of lean construction methods to improve efficiency. According to Stevens (Matt Stevens, 2013), the main reason is that construction companies, because they make little profit and are exposed to considerable risks, do not invest as long as there is no evidence of the benefits. He also believes that there is no *single measure* available to construction companies to compare their efficiency, so that they have no incentive to switch to lean construction methods.
The second reason concerns production processes, where *measuring* results is again an important factor. Our research is based on the method used by Womack et al. to determine the differences in production between assembly plants in their study of the car industry (Womack et al., 2007).
This entire study has been conducted and written from the perspective of the general contractor.
Figure 1-1 illustrates the lean production process of the general contractor.

The *production control* and *work structuring* bars in figure 1-1 represent production management during the project. Ballard and Howell (Ballard & Howell, 2003) highlight a number of differences between lean and non-lean project delivery (see table 1-1).

Some examples of concepts, techniques and applications to illustrate the actual nature of lean production and the differences with traditional practices include: the Last Planner System of Production Control, Work Structuring through Pull Scheduling, Negative versus

Table 1-1 Lean versus non-lean project delivery (Ballard & Howell, 2003).

LEAN	NON-LEAN
Focus is on the production system.	Focus is on transactions and contracts.
Transformation, flow and value goals.	Transformation goal.
Downstream players are involved in upstream decisions.	Decisions are made sequentially by specialists and 'thrown over the wall'.
Product and process are designed together.	Product design is completed, then process design begins.
All product life cycle stages are considered in design.	Not all product life cycle stages are considered in design.
Activities are performed at the last responsible moment.	Activities are performed as soon as possible.
Systematic efforts are made to reduce supply chain lead times.	Separate organizations link together through the market and take what the market offers.
Learning is incorporated into project, firm and supply chain management.	Learning occurs sporadically.
Stakeholder interests are aligned.	Stakeholder interests are not aligned.
Buffers are sized and located to perform their function of absorbing system variability.	Buffers are sized and located for local optimization.

Positive Iteration in Design, and Application of Lean Rules and Tools to Precast Concrete Fabrication.
This study follows the same structure as Womack's study, *The Machine that Changed the World* (TMTCTW) (Womack et al., 2007). The objective, indicators and benchmarking used in Womack's study can be used for the construction industry too.

1.2 Central research question

The formulated objective leads to the following central research questions:

- Can the method applied by Womack et al. for the automotive industry also be used for building projects?
- What indicators can we use to measure the performance of building projects?

1.3 Methodology

We have taken the study conducted by Womack et al. as the basis for our own research. We explain the elements used in that study along with the associated indicators, and we translate them for the construction industry.
ENCORD's Lean Construction Working Group held three preparatory meetings during which the purpose of the study was explained, and at the third meeting an expert panel was set up comprising members of the Group. The expert panel reviewed the indicators mentioned for buildings in table 2-3 and added new ones over the course of four web meetings and a final closing meeting.

We will first discuss the study by Womack et al. and then translate the indicators from the automotive industry to the construction sector. The second part starts with a general section on expert panels, followed by a look at the activities carried out by expert panels.
The result is a list of indicators for the process of a building project (see table 4-1).
The diagram below illustrates the stages of the study by the expert panel:

Add construction industry indicators to the Womack et al. overview

▼

Discuss the indicators in four web meetings, one element per web meeting

▼

Discuss each element in each group (4 times)

▼

Explanation and discussion of each element together

▼

Joint final discussion of all elements

Figure 1-2 The stages of the study.

2. Womack's study in The Machine that Changed the World (TMTCTW) (Womack et al., 2007)

2.1 Introduction

According to the authors, the crux of Womack's study is that "it tells the story of lean production, Toyota's secret weapon in the global car wars that is revolutionizing the world industry". Comparisons are made between different assembly plants across the globe. These comparisons present the productivity and the quality of the different plants. For the construction industry, it is also interesting to know what the productivity and delivered quality is like for different building projects. The situation the automotive industry was facing at that time is also very similar to the current situation in the construction industry. Table 2-1 on the next page presents the key similarities with the construction industry.

Table 2-1 Comparison Car industry - Construction.

CAR industry in the 1980s	CONSTRUCTION now
The opportunities in the industry at the time.	The current opportunities in construction.
The energy issue at the time and in the future.	The built-up environment is the largest energy consumer.
Little change in production methods in North America and Europe.	Little change in actual production process.
The rapid rise of the Japanese car industry.	Cheap labor from Eastern Europe and other low wage countries.
Erecting trade barriers instead of changing production methods.	Lots of legislation instead listening to the industry.
The fear of an economic downturn.	The fear of an economic downturn, just as we are climbing out of recession.
The insight that things cannot continue as they are.	The insight that things cannot continue as they are. Construction is not recovering yet and it will probably be quite some time before it does.
Essential collaboration between car manufacturers worldwide and governments.	Understanding and collaboration between the construction industry and governments.

Figure 2-1 Division into elements according to Womack et al. (2007).

In short, production methods were no longer up to date and, despite the car industry's rosy future, there were major concerns about the continuity of production, a situation which is not dissimilar to the one in which the construction industry currently finds itself. Based on a belief in the principles of lean production for the construction industry (aka lean construction), the division into elements (i.e. collaboration across the stages of the construction process) and the following statement from the authors: "in this process we've become convinced that the principles of lean production can be applied equally in every industry across the globe and that the conversion to lean production will have a profound effect on human society, it will truly change the world", we were inspired to conduct further research into the performance indicators for lean construction.

2.2 How does the method used by Womack et al. work?

This method utilizes Key Performance Indicators (KPI's). These KPIs are compared in different ways, e.g. by region, country, continent, brand, etc. This leads to a number of findings identifying the best and poorest performance. The best results are then reviewed to determine why production/assembly is so much more efficient. Toyota's productivity or that of affiliated car assembly plants often scores much better than other car assembly plants. These companies have a better way of managing the production process. At Toyota, this is called the Toyota Production System (TPS). In the Womack et al. (Womack et al., 2007) study, J. Krafcik dubbed this management method *lean production*.

2.3 The structure of Womack's research

TMTCTW uses a framework for the organization of the car industry and divides the time spent from designing the car to its delivery into separate elements called the *elements of lean production* (see figure 2-1).

Running the factory. The authors were first drawn to this because this element is the most understandable to most people, assembly is the same everywhere and because Japanese car manufacturers wanted to increase production and so were busy building assembly plants in North America. The measurement parameters used are productivity, quality, errors, etc. (see table 2-3, column *CAR*).

Designing the car is the next element. The most important factor for us is the approach to design; the design is made as per the customer's requirements in collaboration with the supplier and the assembly plant. For the parameters used, see table 2-3, column CAR.

Coordinating the supply chain. Supply chain management can be viewed as demanding innovation that is built on prior changes such as TQM and Just in Time (JIT). The massive task of getting all the different parts in the right sequence, in the right place at the right time is probably the biggest challenge facing the car industry. Henry Ford solved this problem by producing everything in his own company. Alfred Sloan of General Motors did the same, but set up decentralized business units producing parts to be less dependent on suppliers. Largely composite parts are provided by suppliers, who also assemble some of the parts. This stage covers the bulk of the production process (see table 2-3, column *CAR*).

Dealing with the customer. The customer is the most important factor in lean philosophy. Due to the nature of the car, which is traded in repeatedly, the customer approach differs per region and is unlike that of other capital goods, which only need replacing once or twice. This is the end of the production process, but the start of the lean production process. The associated parameters used are shown in table 2-3, column *CAR*.

2.4 Matching the structure of Womack's study to the construction industry

A building site can be seen as a place where parts are assembled and, like an assembly plant, where most of the activities to be coordinated to create the final product are carried out. In theory, every building project is the same; it starts with a foundation and ends with a roof. When a construction firm wants to work abroad, it generally gets to do so on a project-by-project basis. "Projects are temporary production systems"(Ballard et al., 2007). The difference is the location of the activities; in the case of car assembly, work is done in the same place in a factory, e.g. each time the same parts or composite parts are built or dismantled. This fully completes the assembly and the product is ready for the next step. This, it should be noted, presents a major challenge to the construction industry.

In construction, it is very important to adjust the design to the sequence, method, materials and tools is in order to ensure that you end up with a sound process.

The construction industry is also increasingly using supply chain management and working with suppliers/co-makers. Changing customer requirements make it difficult to maintain a good working relationship. New contract types are an important means to optimize the supply chain (Akintoye et al., 2000).
Given the long lifespan of building projects, contacts between the customer and the construction firm will differ from those in the car industry, where cars are traded in every 5-10 years.

2.5 Womack's indicators and construction

We have already looked at the elements used by Womack et al. in terms of the different stages in the construction process. The question now is whether the indicators in the car industry can also be applied to construction. As mentioned already, the indicators used by Womack et al. are shown in table 2.3, column *CAR*.

Table 2-2, column *Building* provides a starting point, which originated from a pilot study.

Table 2-2 Indicators used by Womack et al. versus construction first study.

Parameter assembly plant	Vehicle	Building	Translated to construction
Productivity	Hours/vehicle	Hours/building	Building production
Engineering hours per new car	Hours/car	Hours/building	Engineering time new building
Engineering by suppliers	% Total hours		Engineering by suppliers
Development time per new car	Months/car	Months/building	Development time new building
Supplier proprietary parts (supplier's own parts, e.g. Bosch ignition)	%	%	Supplier proprietary (electricity switch boxes) parts
Black box parts (standard parts)	%	%	Black box parts
Assembler designed parts	%	%	Assembler designed parts
Employees on project team	Person/team	Person/team	Employees on project team
New model	Body types/new car	Variation/building	Standard variation of home
Lead time prototype	Months	Months	Time from design till realization
Lead time start production >>> sales	Months	Months	Time from start till 1st completion
Return to normal productivity after new model	Months	Months	Apprentice time
Engineering change costs as share of total die costs	% total	% total	Engineering change costs of resources (e.g. adjusting steel formwork when casting concrete in situ)
Die development time	Months	Months	Development time of resources (e.g. steel form in construction in concrete)
Die change time	Minutes	Hours/home	Change time important resource (e.g. change steel framework from ground floor to 1st floor)
Lead time new dies	Weeks	Weeks/home	Making new resource (e.g. steel framework)
Number of employees on project team	Employees	Employees	Number of employees on the project team
Supplier share of engineering	% total	% total	Supplier share of engineering
Ratio of shared parts	% total	% total material costs	Use of standardized products
Job classifications	Number	Number	Producing suppliers
Machines per employee	Number	Hours/€	Machine application in hours and €
Inventory levels	Days	€	Inventories
Inventory level for eight parts	Days	Days/object	Inventories for essential material (e.g. casing, lime components, wooden beams, sheets of wood, mortar in bulk)
Daily JIT deliveries	Number	Number	Daily JIT deliveries (e.g. ready mixed mortar for concrete and brickwork, prefab floor slabs, prefab floor-laying, hinge roofs, etc.)
Proportion of parts delivered just-in-time (JIT)	%	%	Proportion of parts delivered JIT of total delivery
Proportion of parts single sourced	%	%	Proportion of parts single sourced
Car sales per dealer	Number	Number	Built homes per contractor
Production and capacity vehicles	Number	Number/company	Production of homes per company

Production and capacity engines	Number		
Production per location	Number	Number/region	Production per location
Quality	Defects/vehicle	Defects/building	Points at completion
Ratio of delayed products	1 of ....(number)	1 of.......(number)	Delay in design of building
Return to normal quality after new model	Months	Months	Return to normal quality
Parts defects	Number/car		Points at completion caused by suppliers
Production space	m²/vehicle/year	m²/site	Area of building site
Repair space	% assemblage space	% repair space	% repair time of the points of completion
Teamwork	% workforce	% workforce	% of workforce by suppliers
Component suppliers assembly plant	Number	Number	Component suppliers (e.g. windows including glazing)
Job rotation	No. >>>frequency	No. >>>frequency	Number of different suppliers
Ideas	No./employee	No./employee	Suggestions per employee
Roles	Number	Number	Number of roles of own employees
Training production employees	Hours	Hours	Training of new production employee
Absenteeism	Days	Days	Absenteeism, illness and days off
Welding	% direct steps	Structure	Structure % of total building
Painting	% direct steps	Finishing	Finishing % of total building
Assembly	% direct steps	Assembly	Assembly % of total building
Engineering performed by suppliers (% total hours)			
Supplier proprietary parts			
Black box parts (%)			
Assembler designed parts (%)			
Number of suppliers per assembly plant			
Inventory level (days, for eight parts)			
Proportion of parts delivered just in time (%)			
Proportion of parts single sourced (%)			
Assembly plants (production and potential capacity) (% of total vehicle built at place of final assembly)			
Engine plants (production and potential capacity)			

Legend

Parameter managing enterprise	**Parameter design**
Parameter customer	**Parameter assembly plant**
Parameter supply chain (comparison suppliers)	

How do we read these indicators from the perspective of a builder and what would the equivalent indicators be?

Table 2-3 Indicators used by Womack et al., (Womack et al., 2007) and construction.

	CAR	CONSTRUCTION
Realization	**Productivity** (hours/vehicle)	Productivity hours/building
	Quality (assembly defects/100 vehicles)	Defects/completion
	Space (sq. ft./vehicle/year)	Building site (all costs/m²/week).
	Size of repair area (as % of assembly space)	Extending building site costs (as % of total site costs)
	Absenteeism	Absenteeism
Product development	Engineering hours/10³ cars	Engineering hours/home
	Development time/car (months)	Development time/home
	Employees/project team	Employees/project team
	Supplier share of engineering	Supplier share of engineering
	Ratio of delayed products	Ratio of delayed products
	Die development time (months)	Special resource development time
	Time from production start to first sale (months)	Time from production start to first sale (months)
Suppliers	Die change time (minutes)	Special resource change time
	Lead time for new dies (weeks)	Lead time for new resources
	Machines/employee	Employees/machine
	Inventory levels (days)	Inventory levels (days)
	No. of daily JIT deliveries	No. of daily JIT deliveries
	Parts defects/car	Defects/completion
	Engineering performed by suppliers (% total hours)	Engineering performed by suppliers (% total hours)
	Suppliers/assembly plant	Suppliers/building site
	Inventory level (days, for eight parts)	Average inventory level €
	Proportion of parts delivered just in time (%)	Proportion of parts delivered just in time (%)
	Proportion of parts single sourced (%)	Proportion of parts single sourced (%)
Customer	Car sales/dealer	Home sales/franchiser

Now that we have outlined an initial set of equivalent indicators for (lean) construction, the next question is: how could we verify and supplement them in a sound manner?

3. Expert panel

3.1 Definition of an expert panel

An expert panel comprises a number of people who have extensive skills or knowledge in a particular field (Slocum, 2003). The description used by the Joint Research Centre of the European Commission states: “The expert panel method is based on the idea of eliciting expert knowledge”. There are several forms of composition for expert panels.

3.2 Task of an expert panel

Usually, the main task of an expert panel is to synthesize a variety of inputs, e.g. testimony, research reports, the output of forecasting methods, etc., and produce a report that presents a vision and/or recommendations for future possibilities along with the requirements for the topics being analyzed. Specific tools may be employed to select and motivate the panel, to assign tasks and to encourage the sharing and further development of knowledge (Slocum, 2003).

3.3 When can an expert panel be used

Expert panels are particularly useful for issues that require highly technical knowledge and/or are highly complex and require the synthesis of experts from different disciplines. This method is not designed to actively involve a broad selection of the public (Slocum, 2003).
The result of the expert panel's assessment is expressed in a revised list of indicators.

3.4 Composition of the expert panel

The panel comprised members of ENCORD's Lean Construction Working Group. ENCORD is the European Network of Construction Companies for Research and Development. The panel members come from over all Europe, have a third level education and are all involved in lean construction in a professional capacity.
The panel members meet the above-mentioned requirements as can be seen in table 3-1.

Table 3-1 Members of the expert panel and their expertize.

Your specialist field (tick off)								Your company name	Education	
Residential	Non-resid.	Civil	Bridges	Roads	Railroads	Supplier	Education		According to the Dutch system	
GROUP 1 - RED										
		X	X	X				Ballast Nedam	IR.	Lean Manager
X		X						Hochtief Solutions	DR.	Head of Quality and Lean Construction
						X		Hilti Corporation	DR.	R&D Trends and Application
		X	X	X	X			BAM Nuttall	IR.	Director of Business Processes/ Sustainability
	X	X	X	X	X			CCC	ING.	Group Plant Manager - Operations
X	X	X	X	X	X			Vinci	DR.	R&D Coordinator
GROUP 2 - ORANGE										
		X	X	X	X			BAM Nuttall	IR.	Head of Quality
		X	X	X	X			Strabag	DR.	Business Unit Manager - Lean Construction
		X	X	X	X			Züblin	IR.	Project Manager - Planning
		X	X	X	X			Ferrovial	DRS.	Project Manager- R&D
GROUP 3 - BLUE										
X		X		X				Züblin	IR.	Project Engineer - Work Preparation
X	X							YIT	DR.	R&D Manager - HVAC Technology
X		X						Hochtief Solutions	IR.	Construction Management - services/ Planning & Logistics
X								BAM Deutschland	IR.	Construction Manager
							X	TU/E	ING.	Researcher/Construction Manager
GROUP 4 - GREEN										
		X						Strabag	DR.	Lean Academy
X		X	X	X	X			Ferrovial	MR.	Head of International Projects - R&D
	X							NCC	DR.	Manager of Process Development/ Researcher
		X						GTM	IR.	Manager of Integrated Quality
	X							GTM batiment	ING.	Lean Construction Manager
							X	BAM/TU/e	PROF.	Strategy/Building processes

3.5 Web meetings

Table 2-3 should be taken as the starting point for the work done by the expert panel.

Given that the experts work in different fields, we took the opportunity to distinguish between the different types of construction (projects). The new groups are: residential, non-residential, civil engineering, bridges, roads and railroads. The indicators we were most interested in were those related to efficiency and effectiveness. There may be a lot, but they can later be pooled. The elements relating to efficiency primarily concern the following: labor, material, equipment and sub-contractors. Capital is of course an important factor too and is also mentioned by Womack et al. (Krafcik, 1988).

During each web meeting we addressed, discussed and supplemented one of the following stages:

- **Assembly plant - construction site**
- **Product development - design**
- **Suppliers - partners - co-makers - subcontractors**
- **Customer**

The following question was also asked: how could we measure the value of the indicators? The four interim results were combined, weighted and supplemented later on in a plenary meeting of the expert panel.

4. Results

Table 4-1 Final list of indicators for ENCORD members from the *lean meeting in Paris on March 19-20, 2013*. The different colors refer to the separate discussion groups.
The results are a direct representation of what was discussed in the four groups, so there may be duplications.
Text in red means group RED, text in orange means group ORANGE, text in blue means group BLUE and text in green means group GREEN.

Table 4-1 Shows the overall result of the meetings.

Please note that this is one table although it is spread over the following pages.

ASSEMBLY PLANT - CONSTRUCTION SITE		
CAR assembly	**BUILDING construction**	
	What and how to measure	**What to measure during the process**
Productivity (hours/vehicle)	Productivity hours/building. This measure is usually expressed as total costs/total labor costs. Another possibility is the productivity per part of a project, e.g. foundation, skeleton, outside walls, etc.	Labor, direct* and indirect** working hours, time. *=directly spent on the product, **=indirectly spent on the product.
	Labor turnover (literally staff changes, but we meant total costs of labor in €). You can also relate these costs of labor to the total processed project costs. Also regarding the direct and indirect costs.	Total of labor costs. Total project costs processed.
	Takeaways. Make a record of the number of takeaways related to something going wrong (= failures/defects) or record the training opportunities.	Number of defects. Number of training opportunities, e.g. toolbox meetings, explanation when using new equipment, machinery or methods.
	Measuring labor stability - same employees as week before. This is in fact labor turnover.	Number of employees and staff changes.
	Constructability.	
	Reach objectives.	
	Time spent on looking for material/ equipment.	

ASSEMBLY PLANT - CONSTRUCTION SITE		
CAR assembly	**BUILDING construction**	
	What and how to measure	**What to measure during the process**
Flow indicator		
	No waiting time.	Waiting time can arise because of missing materials and equipment or if a previous activity is not finished on time.
	Changes to schedule. Changes to schedule. Plan changes.	The reason for the changes, e.g. caused by the client (e.g. waiting for information or changing the plan) or by the contractor (e.g. poor scheduling, making mistakes, not enough staff, the wrong staff, etc.).
	Plant turnover.	Manufactured in €.
	In relation to equipment.	Machinery time used.
	In relation to situation (point and line project).	The situation of the site and the government regulations for the area must be considered when setting prices. There are a lot of parameters. Perhaps it is possible to weight every parameter and come up with one indicator.
	Weekly completion in %. PPC value in %. Stages of production.	Completed activities.
	Re-do work. Re-do work. Re-do work. Cost of rework. Cost of defects.	Labor time and material costs. Number of incorrect constructions.
	Could be measured by categorized queries in day sheets.	Queries on rework.
	Additional work.	Amount of labor and material.
	Different phases of delivery.	JIT deliveries.
	Balance of performance-based salaries.	Manager's performance in terms of trying to keep to previously made agreements. A well-thought-out salary system.
	Measure of time lost on machines or because of road work.	Amount of time lost on machines or because of road works.
	Develop a scanning system for the delivery papers.	Paper flow.
	Lost time quality audits (e.g. twice a week to measure lost time according to various criteria. What are the defects, where, etc.?)	Variations.
	Competition, who is the best?	Depends on the group.

ASSEMBLY PLANT - CONSTRUCTION SITE		
CAR assembly	**BUILDING construction**	
	What and how to measure	**What to measure during the process**
Quality (assembly defects/100 vehicles)	Defects/completion.	Not applicable.
	Not only at the end.	Number of defects after a completed activity. And repair time.
	For every milestone.	Number of defects by a defined point of time. And repair time.
Space (sq. ft./ vehicle/year)	Building site (all costs/m²/week).	Site costs.
	Difference in % between residential, non-residential, bridges, roads and railroads.	Site costs.
	Non-conformities.	Number and costs to repair.
	Transparency.	Extensive site administration.
	Quality, time, costs.	Extensive site administration.
Size of repair area (as % of assembly space)	Increasing site costs (as % of total site costs).	Overrun time due to different delays related to lead time.
Absenteeism	Absenteeism.	Staff absenteeism, are they really sick or is it the kind of work?
	Safety on site.	Building site registration.
		Number of accidents.
		1-3 days off work.
		More than 3 days off work.
		Death/invalid.

PRODUCT DEVELOPMENT - DESIGN		
CAR assembly	BUILDING construction	
	What and how to measure	What to measure during the process
Engineering hours/10^3 cars	Engineering hours/(home) per value of project.	Engineering hours spent on a project.
	Value of the project in € (£).	Total of engineering costs.
	Distance for road and rail construction.	Specific measure of the project.
	Relationship between engineering and construction.	Engineering costs versus construction costs.
	Number of standard details versus specific details.	The proportion of standard details versus specific details.
	Energy (CO_2).	Special preparations to reduce CO_2 in engineering time.
Development time/car (months)	Development time (design and planning)/home.	Development time per project.
	The number of changes in design after final design.	Design changes after final design.
	By the customer (failures, mistakes.)	Design changes due to design mistakes.
	By the environment.	Design changes due to the environment.
	Revisions per drawing during and before construction.	Revisions per drawing during and before construction.
Seek additional information	Missing measures on drawings.	Missing measures on drawings.
	Delivery design in time. Late delivery of supplier's design.	Milestones.
	No changes in schedule.	Number of changes.
	Clash detection.	Number of clashes.
	At a certain point in time: final design=no changes. Up to that point, any changes should add value.	To assess by collaborate design and define the milestones.
	Coordination with all disciplines.	Lead time of the collaborate design.
	Time of revision before and after approval.	Days of revision.

PRODUCT DEVELOPMENT - DESIGN		
CAR assembly	**BUILDING construction**	
	What and how to measure	**What to measure during the process**
	We need a plan of the plan.	Headlines and structure of the project. Days of overrun according to schedule.
	Only start construction after a complete plan.	Define this time and use extra time to make the plan complete for all members.
	Measure changes.	Number of changes.
	Focus on the process. Number of defects.	Value stream mapping to draft an appropriate schedule. Number of differences.
	Quality lost.	Specification of quality and inspection. Number of differences.
Employees/ project team	Employees/project team (design team).	Number of employees. Eventually per expertise.
	Value of the project (£/ €). Report differences.	Together with a project category as a rough draft. Project category and value of the project.
	Projects per employee.	Is an indication of the size of a specific part in the design. It also says something about the project. Time spent.
	Costs saved on site/plant through good design/engineering.	Difficult to measure. Compare money and time from the calculation with the real construction. The money and time calculated and the money and time actually spent.
Supplier share of engineering	Supplier share of engineering, % of suppliers design.	The advantage is good design because they have the most practical experience with a system. The disadvantage is that it is difficult to compare with other systems. Number of suppliers in design and their trade.
	Number of leading suppliers for the design.	When the suppliers that own a specific part are leading in the design, e.g. an escalator. Number of leading suppliers.
Ratio of delayed products	Ratio of delayed product drawings and other information.	The starting point is the production start date when the design is completely ready. Is there a direct connection with other design disciplines? Delay to the critical path. Other delays per supplier.
	The right information at the right time. Waiting time.	Is the information complete and on time (included preparation time? Time overrun. Waiting time.)

PRODUCT DEVELOPMENT - DESIGN		
CAR assembly	**BUILDING construction**	
	What and how to measure	**What to measure during the process**
	Interoperability in % of process covered by BIM.	Has BIM been used and for what parts of the process? What parts of the process are covered by BIM?
Die development time (months)	Special resource development time.	Has the development time for special resources been taken into account? What kind of special resources are used? How? What is their development time?
	Time between development and the start of production.	Design time. Time of start of realization.
Time from production start to first sale (months)	Time from production start to first sale (delivery).	This can only be used for homes and other repeatable construction processes. What is important is the time when the production process is running properly, no initial failures. For first sale read first delivery; this means the product development is correct for realization. Improvement of the realization process can start. Production start time. Time until the first completed delivery of a unit.
	Quicker with same resources, no use of additional resource.	Are resources standard or custom made for the project?

SUPPLIERS - PARTNERS - CO-MAKERS - SUBCONTRACTORS		
CAR assembly	**BUILDING construction**	
	What and how to measure	**What to measure during the process**
Die change time	Special resources change time.	
	Material/equipment suitable for site/ plant.	The idea is to use as much standard material and equipment as possible. Standard equipment in hours or €.
	Modular design.	Modular design can minimize the need for more and different kinds of equipment. Use modular design.
Lead time for new dies	Lead time new resources.	How much time does it takes before special equipment is ready? Production time for special equipment.
May not be suppliers better in building sites	Adapting resources (e.g. formwork).	This remark is logical, but when using special equipment this often happens with specialized companies. Adapting time.
	Re-handling materials on site.	Try to deliver JIT as much as possible. JIT deliveries.
	One schedule for every discipline (suppliers, designers, contractors).	Detailed schedule, but do not forget interdependence.
	A more quality schedule.	LPS is the best guarantee for quality, because every party is involved. LPS sessions.
	Number of tasks in a schedule/number of suppliers.	What part of the project is done by suppliers? Number of suppliers, work done by suppliers.
	What can the supplier do to improve the results of the whole project?	Work as if they are part of the company, not only thinking of their own profits. This means minimizing waste and ensuring continuous improvement. Improvements and the profit of improvements. Try to record them accurately.
Machines/ employees	Machines/employees.	For insight into the flow of a product. The machines can also be replaced by activities. Number of times this occurs.
	Workers/employees.	If there are more employees (team) per machine, then it is important to study this situation. Perhaps it is easier to reduce the number of employees. For employee you can also read activity. Number of times this occurs.

SUPPLIERS - PARTNERS - CO-MAKERS - SUBCONTRACTORS		
CAR assembly	**BUILDING construction**	
	What and how to measure	**What to measure during the process**
Inventory levels (days)	Inventory levels (days or €) on site or assistance site.	What is the minimum of inventory required to ensure a continuous process? Inventory level.
The relationship, connection is important	Schedule the JIT>>> draw up a timetable. Handling of materials/equipment in the supply chain. Depends on: storage area, how often you need the material, risk and delivery time (criteria) of the materials.	Material and resource schedule. Number of defects over time.
	Rework.	Try to prevent (stop) rework by automation. Try to stop and repair rework as soon as possible. Number of rework instances. Cost (€) of rework.
No. of daily JIT deliveries	No. of daily JIT deliveries (incorrect and damaged deliveries).	JIT deliveries are only possible when the schedule is managed and updated on an ongoing basis. Number of defects over time.
	Late deliveries.	Quality of deliveries, in time, incorrect, damaged. Number of incorrect deliveries.
	Long-term partnership.	Comakership is a very good way to work together because of the open contact and the longterm contact. Number of comakers and trade.
Parts defects/ car	Defects/completion.	This indicator is used a lot. The advantage is that it only counts at the end of the process. Number of defects. Cost of repair. Time of repair.
	Defects during the process (time, costs, number). How many defects? Not only for the suppliers.	Defects during the process tend to be much more expensive than at completion. Number of defects. Costs of repair. Time of repair.
	Chain of subcontractors (sub, sub, sub).	When poor agreements are made this can lead to problems, a situation that can be seen more and more. Number of suppliers and sub - suppliers.
	Number of defects>>>in relation to zero defects.	This Six Sigma approach matches the above parameter; defects during the process.
	Continually improve.	Treat suppliers as if they were your own staff and support them. Use performance interviews to do so. Calculate scores using performance interviews.
	Number of standardized levels of quality control.	Quality control is most valuable when quality has been defined before. Deviations can be recorded. Number of quality deviations.

SUPPLIERS - PARTNERS - CO-MAKERS - SUBCONTRACTORS		
CAR assembly	**BUILDING construction**	
	What and how to measure	**What to measure during the process**
	Job satisfaction.	A very important item. One of the indicators is absenteeism. Performance interviews can be held for the staff in question. Calculate the results.
Suppliers/ assembly plant	Suppliers/buildingsite specialization.	
	Suppliers/supplier, chain of suppliers, team approach.	When poor agreements are made this can lead to problems, a situation that can be seen more and more. Number of suppliers and sub - suppliers.
Inventory level (days, for eight parts)	Average inventory level €.	What is the average inventory level? Inventory level.
	Common goals/objectives.	These goals can be set if there is a good scheduling system.
	IPD share profit/costs.	What is the relationship between costs and profit, between JIT delivery and the average inventory level? Costs of average inventory. Costs of inventory when using JIT as much as possible.
Proportion of parts delivered just in time (%)	Proportion of parts delivered just in time (%).	Number of parts delivered JIT.
	Complaints against each other.	
	Type of contract.	The type of contract establishes how free the contractor can be in their actions. In a traditional contract, everything has been specified. Freedom of action should be seen as a good way for the company to choose the most efficient way of construction that suits the company. Type of contract.
	The impact of materials that are not delivered on time (software- based).	Value stream mapping to identify this. Number of missing materials and services. Cost of missing materials and services.

SUPPLIERS - PARTNERS - CO-MAKERS - SUBCONTRACTORS		
CAR assembly	**BUILDING construction**	
	What and how to measure	**What to measure during the process**
Proportion of parts single sourced (%)	Proportion of parts single sourced (%).	Parts that need special treatment not suitable for the normal process. Number of parts single sourced. Cost of parts single sourced.
	Reliability of what is promised (delivery time).	Can you count on the supplier? Here, the co-maker is important because they have more of a connection with the company. They consider the long term. Number of deliveries of materials and services not in time. Cost of late deliveries.
Communica-tion	Communication: what is efficient for supplier/subcontractor?	Efficiency can be translated, so that work can be done in as little time and using as little money as possible. That is why it does not make any sense if it concerns the contractor, supplier or subcontractor. In practice, a supplier needs all the information in time and a healthy working relationship with the other parties. Issues with information delivery.
	Orders/day.	To me, orders a day seems more like something for small suppliers working per hour. However, maybe it means that receiving too many instructions every day at one time makes it difficult for the staff to remember and that this is why they will sooner make mistakes. Orders per time per employee.
Flow	Flow: batch versus one piece.	A batch is a manageable group of goods produced in one process step. One aspect of flow is individual production, i.e. one piece is finished before another piece is started. One piece flow is in combination with the pull system. An important aspect of one piece flow is the takt time or meter.

CUSTOMER		
CAR assembly	**BUILDING construction**	
	What and how to measure	**What to measure during the process**
Car sales/ dealer	Home sales/franchiser.	Units of production per dealer. From the customer side, you can view the dealer as a project.
	Who is the customer?	A customer or client is a person or organization that receives goods or services from another person or organization. Take a look at your customer and find out what they really want and what you can do for them. Ask the customer.
	What are our goals? Do all goals lead in the same direction?	There is one primary goal, a satisfied customer. This goal can be divided in several sub-goals, depending on the current status of the company. Toyota sets a much larger goal and thinks of the company and its staff in the future.
	What are the common goals?	Whose common goals? Departments, suppliers and staff, etc. should all share the same goal, i.e. to have a satisfied customer.
	END USER is not known with all kinds of issues.	The end user must be seen as the customer. They must get what they expect or may expect in the light of what is normal or what they pay for.
	CLIENT is the one who is paying you.	They have different expectations than the customer/ end user. Although their expectations are different, they must also get what they expect to get from their customers. You have to investigate what this is. You can do it before or after you work together. Client <> Customer?
	Client represents the end user and vice versa.	The client has to take two interests into account.

CUSTOMER		
CAR assembly	BUILDING construction	
	What and how to measure	What to measure during the process
	Lost, quality, time, defects, claims, safety, environment.	All of these indicators are required to be able to define the customer value.
	Certification, references, sustainability with other projects.	
	Local employees, production and impact or intension.	
	Link budget-schedule.	
	Profitable turnover.	
	Understanding of needs.	
	Transparency with the client.	
Recommendation score:	From 1-5 on the Likert scale.	This is a way of expressing the value of the customer.
	Own contribution.	What is a customer willing to do on their own?
	Demands.	What does a customer ask for?
	Expectation.	What does a customer expect?
	Count the number of meetings with the customer to establish expectations.	All of these points are merely further interpretations of the above-mentioned points.
	Depends on stage of the construction process.	
	Indicator following orders.	
	Satisfaction for the customer/client.	
	Service is important.	
	Questionnaire about satisfaction.	

CUSTOMER		
CAR assembly	BUILDING construction	
	What and how to measure	What to measure during the process
	Delivery on time/earlier.	
	Client involvement.	
	Trust, clear and stable.	
	Progress.	
	Finance: within budget.	
	In a perfect world, a lean organization can deliver a better, faster and cheaper project.	
	Long-term customer/client image.	
	Service.	
	If client is happy, they will come back.	
	Measurement of complaints.	
	Time to being resolved (standard process).	
	Response time.	
	One contact person for the customer.	
	Service for operation.	
	Major difference, customer tells us what to do in a more unique way.	
	Number of change orders.	
	In the construction process, impact decreases with time depending on how far down the line you are.	
	Think also about the internal customer.	
	How do we measure demands, expectations and satisfaction internally?	

5. Conclusion

The method of measuring and comparing used by Womack et al. (Womack et al., 2007) in their study, and which is outlined in the book TMTCTW, can also be used for building projects. The extensive list of indicators drawn up by the expert panel shows this.

As indicated by Womack et al., the advantages they found for assembly plants are therefore also suitable for application in other all industries, including construction.

The most important indicators for a building project are productivity and quality. In the case of production, we can see that time is the leading factor. In the case of quality, it is cost that is the key factor, while time, again, is a key factor in the case of repairs and stagnation caused by poor quality. In fact, the same characteristics apply for each element. In the case of the customer, the direct impact of these characteristics is the least important, while the indirect impact though pricing is all the more significant.

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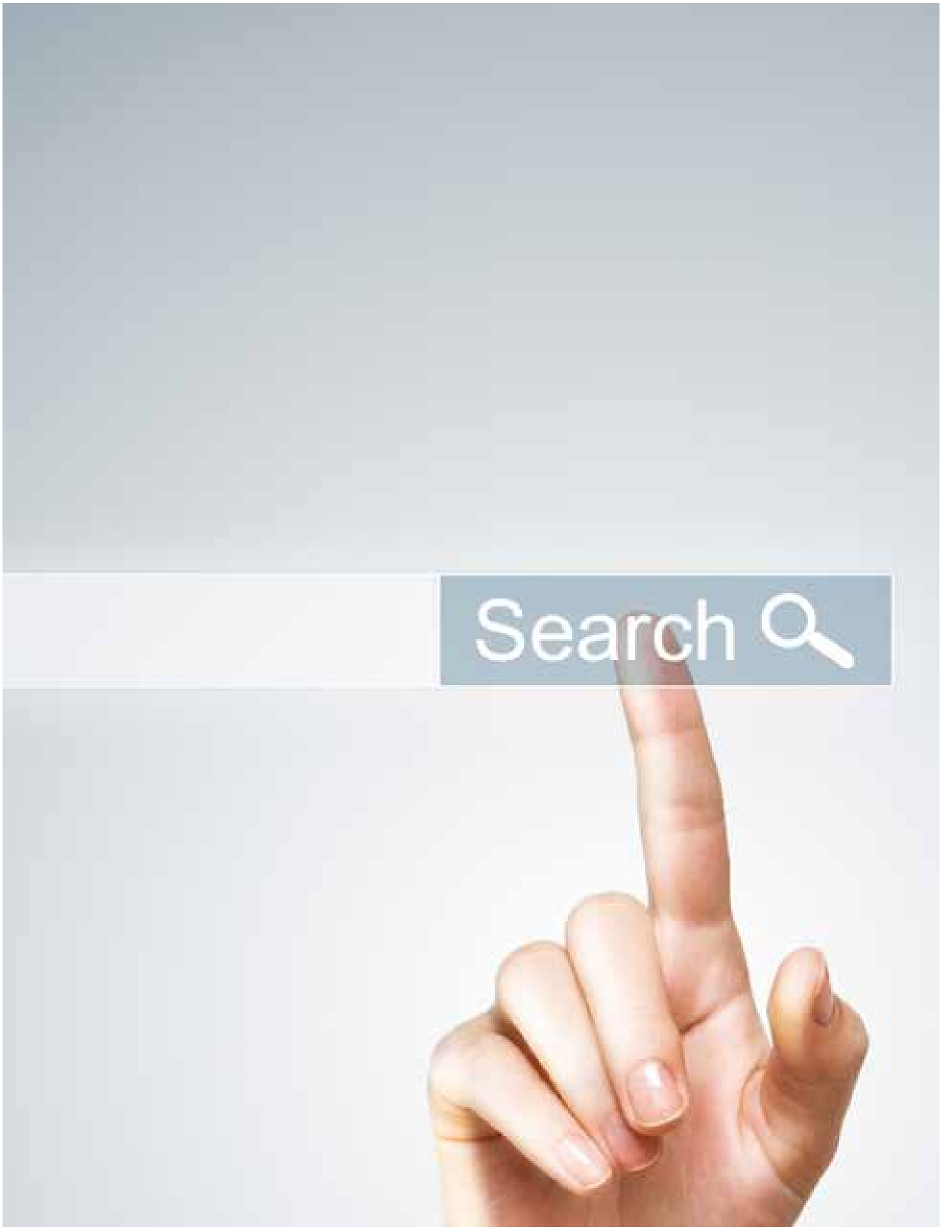
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