IN-SITU CAST CONCRETE BUILDING

IMPORTANT ASPECTS OF INDUSTRIALISED CONSTRUCTION

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ABSTRACT

In the ongoing research programme at Chalmers University of Technology, principles and methods for industrialised building with in-situ cast concrete are investigated. The goal is to increase the understanding of, and to develop methods and systems for, industrial building/construction. Improvement of in-situ concrete construction is necessary; partly in order to meet challenges from other materials. The article deals with questions of how the development should proceed and which research disciplines are needed as support. Opportunities for improvement are identified and a framework for the continuing work has been formulated.
Key words: In-situ cast concrete, innovative building systems, improved concrete construction, cost-effective production.

1. INTRODUCTION

The need for innovative approaches in design and construction is now recognised by most sectors of the construction industry (as stated by the Centre for Innovative Construction Engineering). The construction industry has continuously developed during the years. However, there is need for a fundamental cultural and technical change – we are probably on the verge of a paradigm shift.

There is a need for more efficient and industrialised construction of concrete buildings; this is necessary for the competitiveness of in-situ concrete and essential if the construction industry is to move forward. At present, the expenditure on labour (preparation and dismantling of formwork, reinforcing, and casting and finishing of concrete) almost equals the cost of material (roughly 40 percent is labour). Consequently, the need to reduce the manpower involved is obvious. Development towards 'on-site' industrialisation of in-situ concrete construction presents challenges for all parties involved (i.e. clients, consultants, designers, contractors, and material suppliers). From the viewpoint of structural engineering there is an urgent need to address these problems, to look for innovative design solutions and develop new building/formwork systems. New and efficient permanent/participating formwork systems are likely to reduce arduous and costly labour activities and lead to a more industrialised construction. Apart from development of formwork systems, to reduce the time-consuming activities, there are several other areas for improvement in the concrete industry: buildability; operational methods; logistics and supply chain management; resource allocation; information technology/management, etc. Industrialised construction of in-situ concrete buildings should be seen as an attempt to move from largely craft-based production to a systematic production process where resources are utilised efficiently. Furthermore, it involves the application of modern systematised design, production planning and control as well as mechanised and automated manufacturing processes; see Sarja [1].

A typical building today consists of several standardised and industrially manufactured components (e.g. doors, windows) – components no one would consider manufacturing on site. Building materials, as well, are industrially manufactured in factories (such as reinforcement, prefabricated elements, and ready-mixed concrete, etc). Unfortunately, the industrial production often ends in the factories and the construction, on the building site, is still craft-based production (or manufacturing on site).

2. INDUSTRIALISED CONSTRUCTION

The term 'industrial building' has been used, and abused, ever since its introduction; occasionally it has been used with a negative meaning (for many people the term is inextricably linked to the 1950s and 1960s). To compose a straightforward and clear-cut definition of industrialised building is perhaps not as easy as one might imagine, since different forms and techniques exist. Nonetheless, CIB W24 (International Council for Research and Innovation in Building and Construction, work group 24 [2]) has made an effort and offers the following, quite general, definition:

> ***Industrialised Building*** *is the term given to building technology where modern systematised methods of design, production planning and control as well as mechanised and automated manufacture are applied.*

A comparison between industrial manufacturing and industrial building can further elucidate some aspects and principles which have to be applied in the building industry.

Table 1. Features of industrial manufacturing and the parallels in the building industry, from Girmscheid and Hofmann [3].

Features of industrial manufacturing	Requirements on industrial building
Centralised manufacturing	Prefabrication of building components in factories
Mass production / increased flexibility of production	Development of variable standard components
Manufacturing based on standard solutions and production of variants	Standardisation of building elements with flexibility in the design
Specialisation	Concentration towards certain segments of the market
Integration of planning, manufacturing and marketing	Interaction of planning, design, production, and production processes as well as marketing
Optimised processes and organisations	Optimisation of planning and production processes by considering automation and mechanisation

2.1 GENERAL VIEWS

It is important to make clear that industrialised building does not automatically imply increased productivity, reduction of man-hours, or a better economy. However, it offers these possibilities if a totality concept is applied. Likewise, production indoors, in a factory, can also be craft-based (or manual) which implies that it is not the location that is decisive, but the conditions are important – the benefit in this case is that the workers have a roof over their heads. There is a broad spectrum of techniques available for industrialised building. It is impossible to mention all because, firstly, the techniques are steadily under development and new ones being invented and, secondly, opinions differ on whether a technique is or is not 'industrial'. In any case, techniques mentioned in connection with industrial building include the following:

- standardisation (e.g. components, methods, processes or dimensional standardisation and modularisation);
- prefabrication (manufacturing of components beforehand, similar to off-site fabrication);
- on-site fabrication (manufacturing of components on site or in a field factory);
- pre-assembly (materials, prefabricated components and/or equipment are joined together for subsequent installation);
- modular buildings (units enclosing a usable space and forming a part of the building structure);
- the building system (a product system with an organised entity consisting of components with defined relationships, including design rules);
- mechanisation (the use of mechanical equipment instead of manual labour); and
- automation (utilisation of programmable machines – e.g. robots – performing tasks, or of computerised tools for planning, design and operation).

Most people probably associate industrialised concrete building with precast concrete. It was during the mass production era, in the 1950s, 1960s and 1970s, that the first steps towards more industrialised construction started. Prefabrication is not a novel concept; famous buildings in the ancient world – in Egypt, Greece, and Italy – were erected with prefabricated components made of stone (Warszawski [4]). However, industrialised building does not necessarily equate with mass production – industrialisation can be achieved in one-off projects by adopting system-based solutions. A system-based solution should include a concept of structural elements - which may be project specific - having standard interfaces so that they can be assembled in a simple and standard manner. Furthermore, it should also include predefined manufacturing and construction process - with for instance Just in Time delivery of components.

Prefabrication is appealing because it reduces on-site activities and, thus, eliminates some of the construction peculiarities (e.g. work performed in suboptimal conditions[1]). The concept of prefabrication – as a production system – is good; however, it has various implications for the process. This will not be discussed thoroughly here; for such a discussion see Koskela [5] or Warszawski [4]. It is worth mentioning, though, that the total process[2] tends to be more complex, requirements for co-operation and co-ordination within the design are higher, and the error correction cycle is longer (Koskela [5]). One of the implications is that there is a need, or requirement, to have a quality control system – for all activities during the whole process – in order to eliminate defects and mistakes (or mainly to reduce the variation; 'zero defects' is virtually impossible to achieve). De facto quality control is needed whatever production system or method is used. However, for prefabricated systems and components this is of particular importance, since the requirements on dimensional tolerances are more severe. According to Warszawski [4], the main problem of prefabrication today is the lack of a system approach to its employment among the diverse parties involved.

2.2 INDUSTRIAL IN-SITU CAST CONCRETE BUILDING

To compare in-situ cast and precast building (regarding economy, time, quality, etc.) is not easy – both have their advantages and disadvantages and are needed in order for development to move forward. Precast building, for instance, has the advantage of rapid erection and a fast on-site construction, and the elements are produced in factories, which secures good quality. But on the other hand, it requires a detailed design and connection details are complicated. In-situ cast building has the advantage of easy transportation (the wet concrete), it is flexible when it comes to geometric shapes, it is relatively easy to do late changes to the structure, and the structure becomes monolithic. The disadvantage is the it is produced in an 'unprotected' environment, additional time is required for the drying out process, and it requires more temporary works (like propping).

As mentioned earlier, precasting has some implications for the process and, in a similar manner, so does in-situ casting – and industrialisation results in further implications. In-situ cast construction is a quite complex process with many inputs and flows; e.g. material, components, and equipment have to be transported to and on the site, tasks have to be performed in certain sequences, etc.

One may ask whether industrial in-situ cast concrete building is a paradox, or whether it is sometimes used for marketing purposes as a 'rhetorical' trick. It could be argued that, at times, it is used incorrectly and a more 'correct' term would be mechanisation – the reason for using it might be that it is 'trendy'. On the other hand, that it is a paradox (or a contradiction) is not true – there are no reasons why in-situ cast construction cannot be industrialised. As discussed earlier, the location is not decisive, but the systematised methods are. By improving site conditions, introducing new building systems, and adopting a system approach to its

[1] E.g. climate, congestion, out-of-sequence work, multiple starts and stops, obstructions and interruptions, etc.
2 The process consists of the activities carried out during planing, design, manufacturing, transportation and erection/construction.

employment, industrialisation is a feasible goal. However, it requires that all parties involved (clients, designers, contractors, and suppliers) strive towards the same goal – the goal of industrial in-situ cast construction.

In retrospect to the mistakes made with other forms of industrialised construction (which failed by not including and considering all steps of the process), a totality concept has to be applied. Actually, this necessitates new methods of work as well as a new philosophy for planning, design, and management. There is a tendency among engineers, whether natural or not, to make each beam and column as slender as possible – the smallest size that meets requirements on strength and serviceability – or to minimise the amount of reinforcement. This procedure will result in maximum economy of material but will certainly not result in minimum cost of the finished product – simplicity and repetition are usually the keys to success and the foundation of industrial production. Hence, the designer needs to understand the site activities, have a distinct picture of how the work will be conducted, and know which equipment is available. The designer also needs to comprehend which possibilities are offered and the limitations that are introduced when deciding on a solution. Camellerie [6] declares: *"designers need to orient the design to the men and machines who build the structure and the materials, times, and environment in which it will be built."*

3. IMPROVEMENT OPPORTUNITIES

In the construction industry, it is generally agreed that there are opportunities for improvement and development of concrete construction – the opinions on how to improve, and the means to use, probably differ depending on whom you talk to. Development can generally be divided into two categories: process development and product development. Examples of process development are management, planning, logistics, etc., while product development includes materials, components and systems. For example, research in material science has led to the development of new types of concrete (e.g. self-compacting and high strength) and new types of composite and fibre reinforcement.

If we examine current methods of construction, the problems affecting the construction industry, and the sources causing waste and value loss in a project, the questions arise:

- How should the development proceed in order to realise the full potential of concrete as a construction material, improve the efficiency of concrete construction, and develop concrete construction into an industrial process?
- How could research support this development and which disciplines need to participate – dealing with material, structure, construction, or management?

Today's methods of construction and design of buildings may, in a broad sense, be said to have evolved through the survival of the 'fittest and best' of the methods which have been developed during the years of practice. An example of an innovative product, which has been used for a long time, is the hollow-core slab. However, the current systems have not been developed for the latest material technology or for a mechanised and automated manufacturing process. Furthermore, the advances the industry has made in technology and practice in recent years have largely been ignored in specifications; see Gray [7]. New technologies alter the basis for habitual methods of work, which must be scrutinised without biases, and new ideas and technology should be introduced where appropriate – it is time for a paradigm shift.

3.1 NEW BUILDING PROCESS – A PREREQUISITE!

The current building process is beset by many problems; each of the parties to the process has helped to develop it, but only from his own needs and views, and competition is mainly focused on lowest cost instead of quality, sustainability and customer-perceived value. Thus, the building process is fragmented and the link between the client/end-user and the producer is weak, and the same can be said about the link between designers and contractors.

There is need for a fundamental cultural and technical change of the building process. Currently there is a global trend and it has been recognised that new methods of work are required in order for the industry to move forward, and that client decision-making and design management have to be changed. Best and Valence [8] point out that the cost of design represents only a fraction of the cost of a building over its life cycle – somewhere between 0.1 and 1 percent. It is generally accepted that the major part of the life cycle cost of a building can be referred to decisions made in the earliest stages of the design process; hence the importance of this stage. There is a movement to change the construction process and it has already started, it will fundamentally alter the construction process and, inevitably, increase efficiency and quality. This change is a prerequisite for industrialised construction and for the introduction of industrialised building systems.

The problems in the construction industry have led to governmental reports: e.g. in Sweden, the Swedish Delegation for Construction Cost, SOU 2000:44 [9]; in the United Kingdom, 'Rethink Construction', presented by Egan [10]; and the European Commission's 'The Competitiveness of the Construction Industry' [11]. Brian Atkin asserts that the building industry has a 'best' method of working within reach (SOU 2000:44, Appendix 2 [9]). These reports point out deficiencies in the building industry and give recommendations for a changed project process. Some problems that must be addressed are:

- the industry must replace competitive tendering with long-term relationships based on clear measurement of performance and sustained improvements in quality and efficiency;
- the industry must design projects for ease of construction making maximum use of standard components and processes;
- the industry should create an integrated project process around the four key elements of product development, project implementation, partnering the supply chain and production of components;
- the industry invests little in research and development and in capital. This lack of investment is damaging the industry's ability to keep abreast of innovation in processes and technology;
- the need to focus on life-cycle design and encompass whole-life costs;
- clients need to formulate clearer project goals and specify priorities regarding quality, cost, and time; and
- clients need to understand the importance of the design stage and accept that it requires time.

These governmental reports have, in some countries, led to a response and the launching of action programs (e.g. in the UK: M^4I - Movement for Innovation and the Construction Best Practice Programme; see http://www.rethinkingconstruction.org/).

3.2 TECHNIQUE WITH POTENTIAL

The concrete industry (material suppliers and contractors) is constantly under pressure to improve productivity and reduce costs without lowering the standard of quality of its products. This driving force for technical development has had effects on both concrete and reinforcement technology. The result is new types of concrete and reinforcement as well as new building systems and methods. In a similar manner, the development of information technology (construction IT) has presented new possibilities and methods of work for the planning, design, manufacturing, transport, construction, and operation and maintenance of buildings. In this section a limited number of techniques and research projects will be discussed in order to illustrate the existing potential.

Research reveals that there are considerable improvements to be made by developing and systematising the construction process and the design. A study of the construction process for in-situ concrete buildings was conducted at BRE in Cardington [12]. The current process was mapped, the sources of waste were identified, and an improved process was developed and used. The resulting improvement can be seen in Table 2. These savings have been confirmed by findings in other projects, e.g. the study conducted at the Reading Production Engineering Group; see Gray [7].

Table 2. Potential savings, according to BRE – European Concrete Building Project [12].

Improvement area	**Reduction in total cycle time [%]**	**Reduction in total man-hours [%]**
Supply chain management	10.5	15.0
Buildability	3.0	3.5
Resource allocation	6.5	10.5
Operational methods	8.5	13.5
Total	**28.5**	**42.5**

In a case study of seven construction projects (Burwick [13]) the advantages and drawbacks of participating formwork (precast concrete panels) were investigated. All projects demonstrated time savings of 10 to 35 percent and the system required fewer workers (by 10 to 30 percent). Other advantages were better surface finish (less rework) and improved working conditions. The drawbacks of the system were that material cost was higher, requirements for co-ordination within the design were found to be higher, and dimensional tolerance was more severe. Reinforcement details were not thoroughly planned, and placing reinforcement in walls was difficult.

In a research project investigating rational production systems by utilising self-compacting concrete (SCC) it was found that SCC rationalised production and that the advantages were numerous (Grauers [14]):

- rationalised concrete production, faster construction and less casting time;
- reduction in labour at the building site;
- better working conditions and reduced health problems for the workers;
- good homogeneity, improved quality and durability, and smoother surfaces; and
- easier casting in difficult situations, e.g. complex forms or congested reinforcement.

Today there are several different products, techniques, and materials available for reinforcement of concrete; they are a mix of 'high-tech' and 'low-tech'. Sandberg and Hjort [15] remark: *"at the same time as there are advanced technical possibilities for prefabrication of reinforcement* *much of the work is conducted traditionally and manually (mostly on site) often leading to bad working conditions, poor quality, and a high total cost.”* Nevertheless, the use of prefabricated reinforcement increases and it is a technique for the future – the possibilities to reduce site activities are considerable. An example of an innovative reinforcement system, developed lately, is BAMTEC®, which is a reinforcement carpet for slabs (a production level of 4.5 tons/man-hour has been achieved; see http://www.bamtec.com). Another technique, used more often nowadays, is fibre reinforcement (fibres of steel, carbon, aramide, etc.) which is used for example in slabs, and it is also suitable for thin prefabricated elements as well.

3.3 RESEARCH AND DEVELOPMENT

During the years, research and advances in engineering science have increased our knowledge. Hitherto, among other things, they have contributed to our comprehension of material properties as well as design rules, enabling us to build safe and slender structures. Likewise, the study of scientific management (pioneered by Taylor [16]) has helped us to understand the principles of, and to improve, manufacturing and production. However, as knowledge gradually accumulated, research separated into different disciplines (e.g. of material, structural, construction, and management) and researchers and practitioners specialised. Each of the specialists works with the ambition to do the ‘best’ at his/her part of the problem, but often without considering the whole problem in its proper context, a trend which leads to suboptimal solutions and increases the fragmentation of the industry.

Indeed, there is support for this view – in a study conducted by Josephson and Hammarlund [17], it was found that the main cause of the design defects was lack of knowledge (44 percent). Further, Lautanala [18] states that considerations of constructability are based only on the designers’ personal experience from construction. Consequently, since their knowledge is based on experience rather than scientific study, designers have problems in addressing constructability and, when they do so, it is with varying results. De facto, designers need feedback from, and a dialogue with, the contractors who are experienced in construction technology and meet the problems on a daily basis. Ballesty [19] states that designers often have to rely on anecdotal or *ad hoc* feedback rather than analytical assessment of actual performance of facilities. Walraven [20] argues: *“the structural designer and the material scientist are often seen as representatives of two totally independent groups of professionals. This is a wrong interpretation of actual needs, since design of today and tomorrow requires much more than realising structures with sufficient safety against overload.”* Walraven [20] continues: *“a structural engineer who is ignorant about the ‘ins and outs’ of the material concrete can never be a competent designer.”* Furthermore, Camellerie’s [6] view is that *“in our highly specialised society, we have developed a breed of engineers who can compute and draw, but have only hazy notions of how to build. Structures designed by such engineers are ‘successfully’ completed only after much anguish and modification in the field and at unnecessary cost in time and money.”* There are currently several research projects (information and knowledge management) with the aim of developing methods and systems that will aid designers in the decision process.

Development of construction and building systems may have suffered from this separation. A systematic development of in-situ concrete construction, considering the whole construction process, is needed – development has to be done by unifying the knowledge in the disciplines. Other researchers share this view; Sarja [1] suggests that *“the development of materials and structures will have to be done in close interaction with managerial, organisational and design development. Materials and structures must be designed and be suited for a mechanised and automated manufacturing process and they must be tailored for different requirements.”*

Research and development where problems are isolated from their context should be avoided, since suboptimal solutions are the outcome in most cases.

3.4 NEW TECHNOLOGY – A SOLUTION?

In various studies of the building industry it has been concluded that there are high levels of production waste as well as low productivity (see Table 3). In a project there are several sources of waste and value loss (see Figure 1), and there is an abundance of remedies suggested and used for these problems. The basic solution, though, as suggested by Koskela [21], is to systematically and persistently decrease the share of non-value-adding activities in all processes, and to continue increasing the efficiency of value-adding activities. In the latest decade the construction industry has, among other things, tried to apply management philosophies in order to tackle some of the problems outlined above (e.g. lean construction, value management, total quality management, just-in-time production, process re-engineering). Other methodologies for improvement are, for example: industrialised system building (i.e. prefabrication and modularisation), computer-integrated construction, information technology, automation and robot technology.

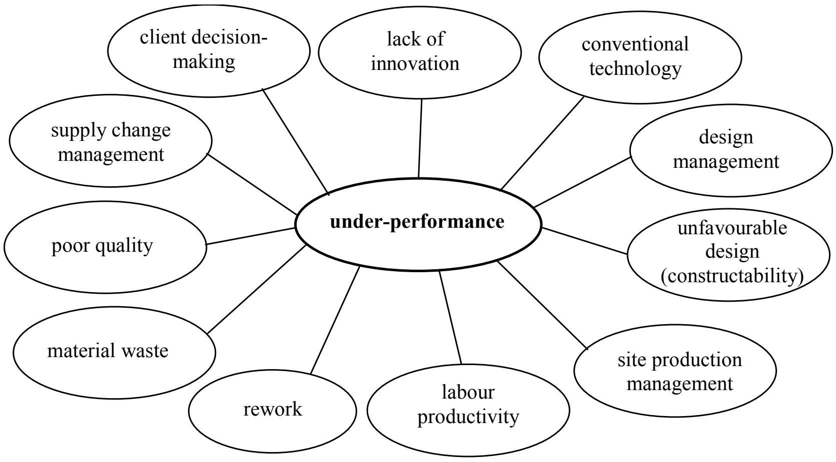


Figure 1. Some of the problems affecting the construction industry.

There is a widespread notion that by adopting state-of-the-art technology, problems will be rectified and an improvement achieved. However, history shows otherwise; Girmscheid and Hofmann [3] remark that industrialised construction often failed by prioritising the production while ignoring product and management processes. Koskela [5] and Warszawski [4] draw similar conclusions. To avoid such mistakes it is important (if not necessary) to study the building process and methods in use today, in order to realise the importance of a totality (holistic) concept – a concept including all steps of the process (i.e. planning, design, manufacturing, transport, erection/construction, and operation and maintenance). In Lean Production, e.g. Koskela [22], it is suggest that major investments in new technology are to be considered only after improving the present process; implementation of new technology is easier in controlled production processes. Or to quote Badger [23]: *"It is relatively easy to create new technology, but the payback remains low until tools and processes are developed and people take ownership of the new knowledge."* It is often neglected, or not properly understood, that many problems are caused by basic structural deficits within organisations (i.e. the management, planning, and methods of work) and cannot be solved solely by means of new technology.

4. CURRENT SITUATION

It has already been mentioned that there are problems affecting the building industry; see Figure 1. By examining these problems a better understanding and increased knowledge of the construction process can be achieved, knowledge which is an essential foundation when adopting new materials or developing new building systems to be used in construction. The first step is to analyse the current construction process with the aim of obtaining a general view of the activities and to identify:

- possible causes of waste and deficiencies;
- management and organisational deficiencies;
- inefficiencies in design (bad constructability);
- inefficiencies in construction methods; and
- improvement opportunities.

One definition of waste is "*all (construction) activities that produce cost, direct or indirect, but do not add value or progress to the product*" (Serpell and Alarcón [24]). On a building site it includes labour, material, and equipment.

4.1 CONTEMPORARY MANAGEMENT OF DESIGN AND CONSTRUCTION

Construction is characterised by a high proportion of non-value-adding activities and low productivity (compared to other manufacturing industries) – Koskela [5] even suggest that there are endemic problems associated with client decision-making, design management, supply chain management, and site production management. Koskela [5] points out some major features of the construction industry:

- work is often done in suboptimal conditions – located on a site and affected by seasonal and climatic variations;
- construction can be conceived as prototype production;
- procurement through bidding;
- institutionalised roles and division of work – multidisciplinary;
- separation of design and construction;
- temporary organisations; and
- long service life.

There is growing dissatisfaction among clients and the authorities are deeply concerned; projects are seen as unpredictable in terms of delivery time and budget, and there are problems with the standard of quality. The client's time schedules, occasionally unrealistic, and lack of time for the design may cause some of the problems. Other causes could be poor planning and co-ordination or lack of information, knowledge, and motivation. The building industry also has a low and unreliable rate of profitability. As a result, it is sensitive to economic fluctuations and, consequently, invests too little in research and development.

Several studies of the construction industry have pointed out shortcomings that urgently need attention. Recent studies in the USA and UK suggest that up to 30 percent of construction is rework, labour is used at only 40 to 60 percent of potential efficiency, accidents can account for 3-6 percent of total project costs, and at least 10 percent of materials are wasted; see Table 3. In numerous studies from different countries, the cost of poor quality, as measured on site, has turned out to be 10 to 20 percent of total project cost (Cnudde [25]). Furthermore, the increase in efficiency in the construction industry lags behind other manufacturing industries. Between

1965 and 1996 the increase in productivity in Sweden was only 2.6 percent per year in the construction industry, compared to 3.9 percent per year for other industries; see SOU 2000:44 [9].

Table 3. Compilation of Data on Construction Waste, from Koskela [21].

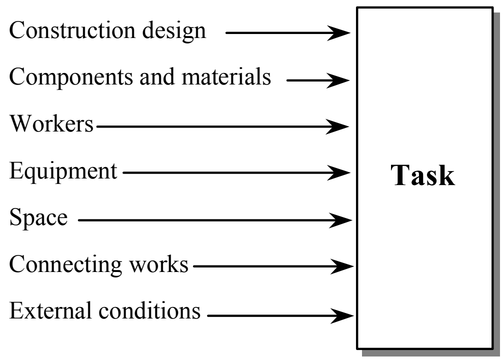
Waste	Cost	Country
Quality cost (non-conformance)	12% of total project costs	USA
External quality cost (during facility use)	4% of total project costs	Sweden
Lack of constructability/buildability	6-10% of total project costs	USA
Poor material management	10-12% of labour costs	USA
Excess consumption of materials on site	10% on average	Sweden
Working time used for non-value-adding activities on site	App. 2/3 of total time	USA
Lack of safety	6% of total project costs	USA

The conventional building process is generally sequential because it reflects the input of clients, architects, designers, contractors, and suppliers. Several researchers (Koskela [21] and Dupange [26]) have pointed out that sequential design leads to unsatisfactory performance: there are few or no iterations in the design process, constraints of subsequent phases are not taken into account in the design phase, and unnecessary constraints for subsequent phases are set in the design phase. Furthermore, there is little feedback for specialists and there is a lack of leadership and responsibility for the total project. Consequently, the sequential procedure leads to:

- suboptimal solutions;
- poor constructability and operability;
- large numbers of change orders (leading to rework in design and construction); and
- lack of innovation and improvement.

It is important to understand that engineering design is only one phase in a much larger process – but a very important one. Moreau and Back [27] state that the quality and accuracy of the design product can also influence the project schedule and cost (the number of field interferences, the amount of rework required, the optimisation of material resources, and the ease and efficiency of construction). Moreau and Back finally point out that, despite the significance of the design process to the delivery of the constructed facility, the design process is stilled riddled with inefficiencies.

In a case study, conducted by Koskela [5], it was found that waste (non-value-adding activities) primarily originated from prior phases of the project rather than from the phase of its occurrence. Waste was caused by problems of client decision-making; design management; supply chain management and site production management. Particularly client decision-making and design management suffered from lack of planning, resulting in frequent change orders and extra costs. Regarding the site activities, waste originated from rework, waiting, and reduced productivity due to suboptimal conditions. As can be seen in Figure 2, there are seven resource flows (or conditions) that unite to generate the task result. Hence there are many sources of variability, and missing input leading to reduced productivity and the risk of disturbances increases with the number of resource flows. Koskela [5] gives an example:
"let us assume that the probability of a deviation in any of the resource flows to a construction task over one week is 5 %.



For seven resource flows the probability that there is no deviation in any input flow is thus:
Prob{no deviation in any input flow} = $(0.95)^7$ = 0.70

For ten resource flows the probability that there is no deviation in any input flow is thus:
Prob{no deviation in any input flow} = $(0.95)^{10}$ = 0.60"

Figure 2. Preconditions for a construction task, from Koskela [5].

At present, too much time and effort are spent on the construction site trying to make designs work in practice. A study conducted by Josephson and Hammarlund [17], on the cause and cost of defects in construction, showed that the cost of defects during production varies between 2.3 and 9.4 percent of the production cost. An analysis indicates that, on average, 32 percent of the defect cost originates in early phases, i.e. can be referred to the design phase. Approximately 45 percent of the defect cost originates on site, i.e. in relation to site management, workers and subcontractors. About 20 percent of the defect cost originates in materials or machines. However, when measured by cost, design-caused defects are the largest category; of these defects, those originating from missing co-ordination between disciplines are the largest category. When studying the root causes, it was found that about 80 percent of the defects originated from lack of knowledge and motivation.

4.2 CONSTRUCTION COSTS AND DISTRIBUTION OF LABOUR ACTIVITIES

Building costs are a subject that has been studied thoroughly over the years. Several factors influence the total expenditure: material choices, labour costs and the working hours of those involved in executing the work, and cost for machinery used in executing the work. Furthermore, the cost of capital (financing) for the investor as well as the contractor has to be considered.

A comparative breakdown of the construction costs of a concrete building (office or residential) reveals that the superstructure represents approximately 10 to 15 percent of the total cost, a figure which has decreased during the years. The main difference today is that the costs for cladding, finish, and especially service installations have increased during the years. Owners and occupiers today have greater demands and different needs, and they expect higher standards. Best and Valence [8] emphasises the fact that the cost of construction is only a small part of the total cost of a building during its life cycle. The design cost is only a fraction, about 0.1 to 1 percent. This should be kept in mind when considering that roughly 80 percent of the cost is generated by only about 20 percent of the work items required for construction. Much of that 80 percent is related to design decisions made in the earliest stages of the design process.
The costs for the concrete superstructure can generally be divided into formwork, reinforcement, concrete, repair of surfaces, and remaining (e.g. prefabricated elements). The operations involved in traditional in-situ cast concrete construction can be seen in Figure 3. Before the process of improvement can commence, it is necessary to understand the current practice, its process, and the operations (or tasks) involved. Construction data for 11 office- and 16 house-buildings (built between 1989 and 1993) have been compiled by the Swedish Ready-Mix Association [28]. These data have been analysed in order to get an overview of the

distribution of man-hours between the different operations and to get a picture of where major improvements are to be made. The analysed data refer to the relative distribution of construction costs for the concrete superstructure. Table 4 shows the relative expenditure for the concrete superstructure (material and labour costs). As expected, reinforcement and, above all, formwork are the most labour-intensive activities, while concrete accounts for the main part of the material costs.

Table 4. Approximate proportional cost breakdown (material and labour costs) of a concrete structure [28].

	Cost of material	Cost of labour	Total
Formwork	14%	18%	32%
Reinforcement	10%	8%	18%
Concrete	30%	4%	34%
Repair	1%	5%	6%
Remaining	9%	1%	10%
Total	**64%**	**36%**	**100%**

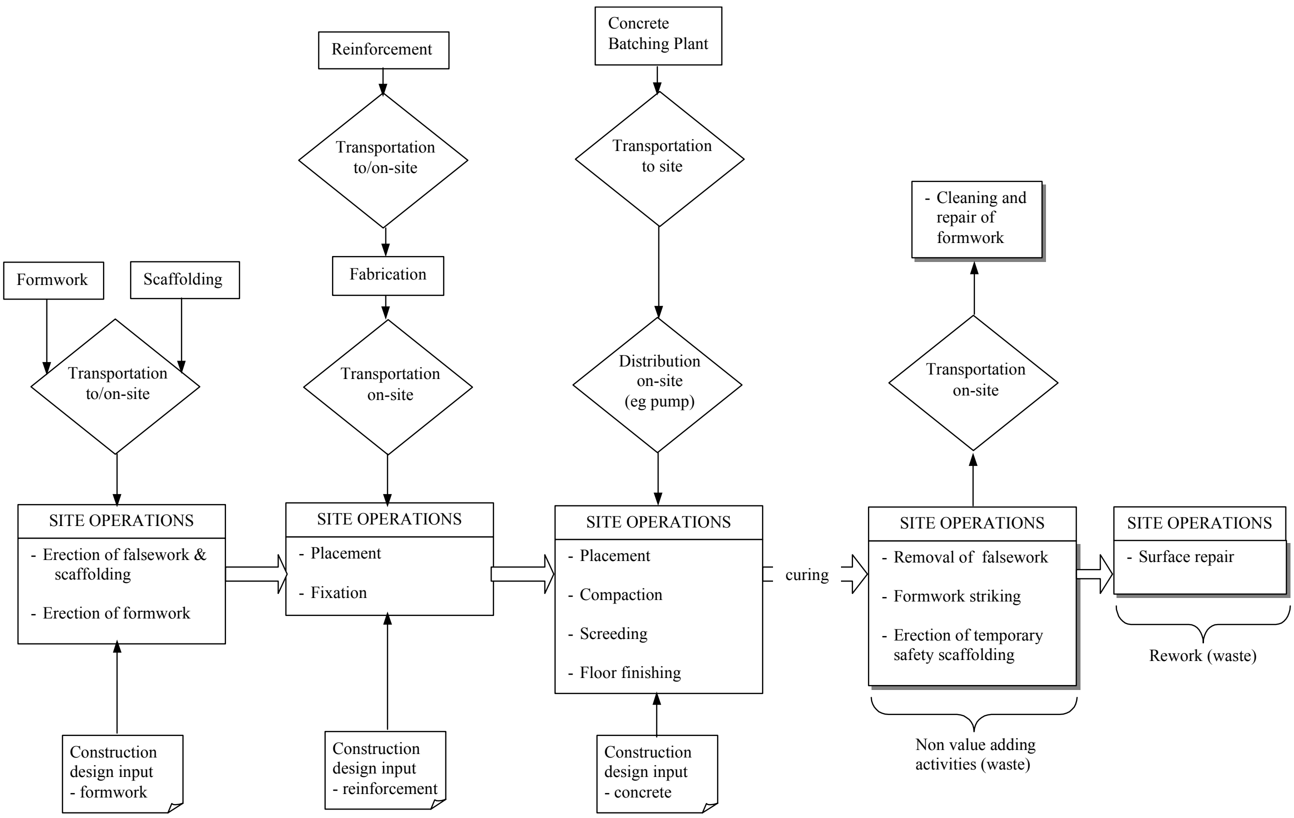


Figure 3. Operations involved in traditional concrete construction (schematic).

The distribution of material and labour costs naturally differs between the projects, and additionally, the market situation affects the price of material and the cost of labour. However, the distribution of labour costs mainly depends on the methods and equipment used in construction, and is not so dependent on fluctuations of the market. Hence, the importance of the tasks is better understood by studying the distribution of man-hours. As can be seen in Figure 4, almost 50% of the total work on a concrete structure can be referred to the formwork; reinforcement operations require roughly 22 percent of the work; while concrete operations represent only 11 percent. On the other hand, if rework to fix surfaces (repair 15 percent) is added, it gives concrete a share of 26 percent.

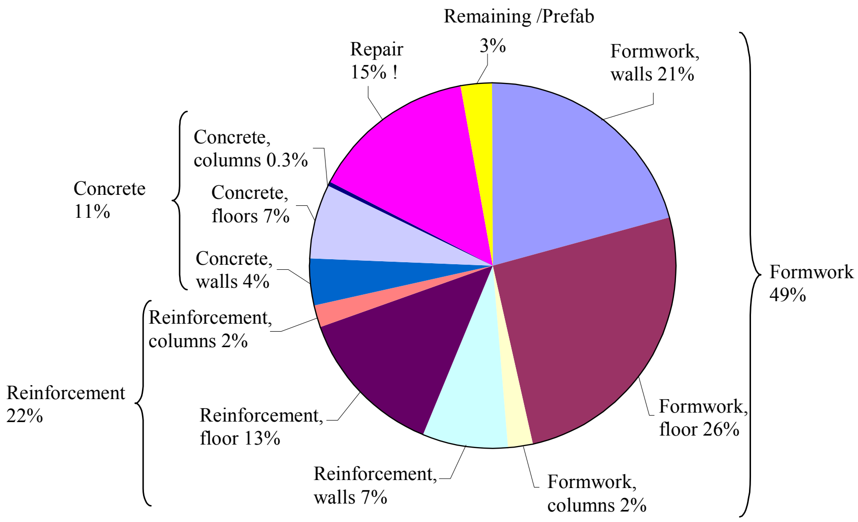


Figure 4. Approximate relative breakdown of man-hours for a concrete structure, average values [28].

By studying the distribution of costs and man-hours we have gained the following knowledge, or rather the notions, mentioned earlier, have been confirmed:

- formwork represents the major portion of man-hours; and
- rework, or repair of surfaces, is quite extensive.

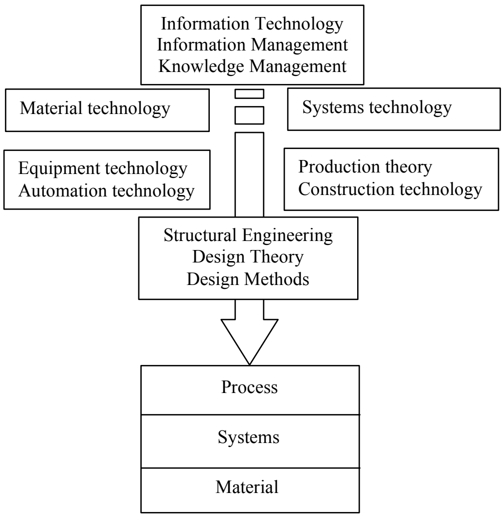
Development of new permanent formwork systems would enable a more efficient concrete construction and render arduous and costly labour activities unnecessary. In view of the advent of self-compacting concrete and fibre reinforcement (techniques that will reduce the labour at the building site) this development seems even more desirable.

5. FURTHER WORK – FRAMEWORK FOR THE DEVELOPMENT

The main objective of this research project is to develop new systems and methods for an 'on-site' industrialisation of construction and to increase the understanding of industrial in-situ concrete construction. The aim is to reduce construction time and the man-hours required to construct. Furthermore, other important aspects that should be aimed for are a reduction of costs, raw material use and energy consumption (both during construction and as an operational building) as well as improved quality and increased customer value.

It can be concluded that there exist considerable opportunities for improvement in the construction industry; thus, these opportunities should be exploited. Some of the deficiencies that have been observed – and brought up in this article – cannot be improved by, or taken into account in, this project. It has also been mentioned that there is need for a cultural change and that client decision-making, design and production management have to be changed. Many of the problems concern fundamental deficits within organisations and methods of work, and thus cannot be solved solely by means of new technology – which is the main aims of this project. However, it is important to point out and call attention to these problems as well as bearing them in mind for the subsequent work. Let us hope that common sense will prevail and that there will be a cultural and technical change in the near future.

On the other hand, some of the deficiencies can be improved and – based on observations of the current process and practice coupled with the analysis of building costs – a framework for the development can be formulated. The framework will act as a general guideline for the development and it stipulates the cornerstones and the basic, underlying technologies; see Figure 5. The following cornerstones have been identified for this framework:



- Process – production theory and construction technology (the repeated processes in construction).
- Systems – systems and automation technology (modularisation and component interfaces).
- Materials – materials technology (development and research).

Figure 5. Basic technologies and framework for development.

In addition to these items, economic and environmental aspects have to be considered. Economy is always a strong argument, and environmental aspects are relevant since there are regulations on materials to be used in buildings (i.e. emissions, energy consumption, recycling, etc).

While the framework and the basic technologies act as a general guideline, specific functional requirements must be formulated, and should be identified from the needs, demands, and wishes of the customers, i.e. not based on national codes and standards. However, the developed systems must of course fulfil the basic requirements in national codes and standards. As mentioned before, all the customers in the supply chain need to be considered (e.g. client, designer, manufacturer, supplier, contractor, and end-user). The functional requirements can be identified in a workshop where people are invited to give their opinions (i.e. representatives from all disciplines and all stages of the process). When the functional requirements have been identified the conceptual stage begins, this is an iterative decision making process where different layouts and feasible alternatives are identified. It is necessary to conduct this thoroughly and systematically; it should be done with the aid of a design system/method in order to handle the requirements and optimise the design. For example, structural requirements (such as strength, ductility and deflections) will be assessed by FE-analysis.

5.1 MATERIAL

New materials, well suited for a mechanised and automated manufacturing process, have emerged from the material researchers. Materials have to be investigated regarding their versatility and their capability to improve; they must be suited for such a process. The concrete industry has developed into a high-tech industry in recent years; progress has been enormous, notably in the improvement of concrete strength. However, it is not only strength that has been increased. Lately other material properties have been recognised as equally important – for example, permeability, ductility, and workability. It is now possible to obtain certain predefined properties by adapting a certain mixture composition; to quote Walraven [29], the era of “tailor-made concrete” has arrived.

Examples of recent material developments are self-compacting concrete (SCC), as mentioned in chapter 3.2, and fibre-reinforced concrete (FRC). Fibre-reinforced concrete has recently enjoyed a breakthrough in the construction industry, with the main application for slab on grade. Yet it is not a 'miracle material' and ordinary reinforcement will still be needed. The fibres are mainly added to control cracking in the service state and to increase the ductility, but not to increase the ultimate limit strength; for safety reasons, reinforcement is added to make sure of the structural stability and ductility in the ultimate limit state. One disadvantage of fibres is that it is difficult to control their distribution, resulting in a fairly high and uneconomical fibre-ratio. Nevertheless, used in appropriate elements, fibres can reduce the amount of reinforcement bars and thus the labour force required. Another development that shows promising results is standardisation and pre-assembly of reinforcement units; it has already become common practice to use prefabricated wire-mesh mats. However, there remains much more to be done in this area.

5.2 PROCESS

It is often claimed that the construction industry is different from other manufacturing industries – every product is unique and in most cases only one prototype is built, the actual building. To some extent this is true, as building designs are unique; the process, however, is essentially repeated from project to project and, indeed, research suggests that up to 80 percent of inputs, design problems and materials in buildings are repeated (Egan [10]). This is important to keep in mind; these repeated 'processes' are one of the basic principles to develop new building systems from. The 'one-off mentality' is something that the industry must abandon if it is to move forward and improve. Projects must be designed for ease of construction, and the knowledge possessed by contractors and material suppliers must be utilised in order to reap the full value, and to be able to realise the potential, of concrete as a construction material.

5.3 SYSTEMS

For the next discussion, a building system can be defined as follows: "a building system includes design rules and a product system whose parts have compatible interfaces, thus permitting the use of several alternative components and assemblies. The compatibility of the components and assemblies is assured by means of a dimensional and tolerance system as well as of connections and joints" (Sarja [1]). Furthermore, open systems have a framework of standards or rules for dimensional co-ordination and compatibility, allowing different systems to be assembled. The systems should be open to (Sarja [1]) free design for varying requirements, free competition between contractors and suppliers, future changes in use, and reuse and recycling. Consequently, design and construction of buildings face multiple requirements which all have to be considered. "The main goal of construction, in all societies, is a good quality of the built environment in terms of aesthetics, health, economy, and ecology throughout its life-span, fulfilling clients' needs and all the requirements of a sustainable society and nature" (Sarja [1]).

CONSTRUCTION METHODS

As shown in section 4.2, the cost of a concrete element (e.g. a slab or a beam) can be separated into the cost of labour (the cost of the employee and the time required to construct it) and cost of the material used. These are the two primary factors which affect the economics of a system. For example, permanent formwork usually reduces site manpower and the floor-cycle time but increases the material cost, as indicated by Burwick [13]. When analysing construction costs from actual projects it was established that formwork is the most labour-intensive activity. Consequently, development of new formwork/building systems has the potential to reduce labour. Concrete construction is a complex process, involving many inputs and flows, and certain operations are involved; see Figure 3. When studying these operations from a perspective of value management, it is clear that erection and dismantling of scaffolding and the stripping, cleaning and repairing of formwork are examples of non-value-adding activities. The operations are necessary for traditional formwork, but they add no value for the end-client. Permanent formwork, for instance, is an attempt to rationalise the construction, and two different types can be distinguished:

- leave-in-place forms, which derive their economy from saving the cost of stripping and cleaning; and
- participating forms, which function as an integral part of the structure when in service; they achieve their economy by saving the cost of stripping and cleaning, by replacing some of the reinforcement, and by composite action adding to the load-carrying capacity.

STRUCTURAL SYSTEMS

When designing structural systems (or choosing between different solutions) the total cost is reduced if the labour saving is greater than the increase in material cost. However, additional savings and benefits might also exist when comparing different systems; unfortunately, these are not always as easy to assess (in the form of a price tag). The benefits may for instance arise from better thermal comfort, superior acoustic environment, flexibility to changes, or easier integration of service installations. Savings may arise from needing less temporary works, achieving an earlier hand over, less overall construction time, less material wastage, less vulnerability to weather conditions, etc. Patrick [30] suggest that because a composite permanent formwork can serve dual roles – firstly acting as the formwork before the concrete hardens and than as a integral part of the structure – economic advantages should result compared using removable formwork systems. For a permanent formwork system to achieve an economic advantage is it necessary that it is utilised efficiently during both the construction stage (as formwork) and the composite stage (in the completed structure). To achieve this advantage an optimisation of structural shape, geometry, thickness of elements, etc. is needed. For this optimisation there are different stages that have to be considered. Patrick [30] identified stages I and II as relevant to the design of the system, stage III is added to complete the different stages that need to be considered.

(a) Stage I – prior to placement of concrete, which includes the time:
  (i) during transportation, handling and erection – e.g. damage during lifting; and
  (ii) once the formwork is erected but prior to placement of the concrete – e.g. deflections and damage from construction loads, temporary stabilisation.
(b) Stage II – during placement of concrete up until concrete hardens – e.g. deflections during casting.
(c) Stage III – during usage of the structure, which includes:
  (i) normal usage (serviceability limit stage) - e.g. deflections, cracks, vibrations, acoustics, thermal comfort;
  (ii) at overloads (ultimate limit state) - e.g. strength, ductility.

These stages are equally important but result in different requirements and loading conditions. Stage I and II involve the safety requirements for the workers during construction. While stage III involve the safety for the end users. However, it is during stage I and II the initial economic boundary is set for the system, i.e. the material and labour costs are spent during these stages.

Industrialised construction requires that some aspects need a more thorough consideration, for example:

- open systems for compatibility of various components;
- optimal combination of materials and production methods – from the viewpoint of structural, construction, thermal, acoustic, etc.;
- optimal combination of in-situ cast and prefabricated components;
- focus on interfaces between various structural components (e.g. connection details and interface between in-situ concrete and prefabricated components); and
- a holistic view on a system level.

5.5 VISION OF THE FUTURE DESIGN

The rapid progress in computer- and information technology has produced a powerful tool for the development of new design methods able of taking more factors into consideration at the same time, and thus giving an overview of the whole building from design to construction. It also gives the opportunity to view different types of design and to see the effects of various concepts, so called "conceptual design". This gives the engineer the tool to think and work systematically in an engineering way and the possibility to simulate the structure during construction as well as during its life cycle. Furthermore, it also opens for optimisation of a structure/building concerning both economical aspects as well as human considerations and wishes, i. e. architectural aspects, comfort etc, and allowing for a more industrialised production.

6. CONCLUSIONS

Current concrete construction and design are meeting new challenges from other construction materials and techniques (e.g. steel, precast concrete, and timber). The 'on-site' industrialisation of concrete construction is intended to address this challenge and the problems affecting the construction industry. A prerequisite for the development of industrial building/formwork systems (and goal for the system) is that 'they should be of fundamental importance for the competitiveness of concrete structures and of great value for the whole building sector'. New building/formwork systems for site-cast concrete structures are expected to have a strong impact on production efficiency and market shares. This development will reduce on-site labour, increase productivity, improve quality, result in efficient material usage, and shorten the time between project commencement and occupation of the building by paying tenants. It will, however, require improved materials as well as a design and construction management which is able to plan and control their use.

To answer the questions in chapter tree of this article (improvement opportunities), the following conclusions can be drawn:

- development should obtain support from all research disciplines (material, structural, construction, and management) – designers, contractors, and suppliers must co-operate;
- how development should proceed depends on whom you are talking to. A shift of paradigms, resulting in a fundamental cultural and technical change of the building process, might be necessary. New building/formwork systems are also needed:
  - industrial construction requires a totality concept which includes all steps of the process;
  - all parties involved (clients, designers, contractors, and suppliers) should strive towards the same goal – the goal of industrial in-situ cast construction;

- development of construction and building systems may have suffered from the separation of research and subject fields, and the industry has become fragmented;
- labour costs represent roughly 40 percent of the construction cost, and formwork accounts for the major portion of this cost (almost 50 percent);
- research confirms that there are substantial possibilities for improvement (reduction of man-hours and construction time as well as improved working conditions) – BRE-Cardington [12], Grauers [14], and Burwick [13];
- waste (non-value-adding activity) primarily originates in the early phases of projects (client decision-making, design, supply chain and production planning) – Koskela [5];
- waste on the building site originates from rework, waiting, and reduced productivity due to suboptimal conditions – Koskela [5];
- studies of the cause and cost of defects in construction showed that 80 percent of the defects originated from lack of knowledge and motivation; there was also found to be poor co-ordination between design disciplines – Josephson and Hammarlund [17];
- it can be stated that today's method of work does not live up to the definition of industrial building, the first deviation occur already at the design stage (where the first defects are 'built in').

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