Construction Management and Economics

ISSN: 0144-6193 (Print) 1466-433X (Online) Journal homepage: https://www.tandfonline.com/loi/rcme20

Defects in offsite construction: timber module prefabrication

Helena Johnsson & John Henrik Meiling

Construction Management and Economics (July 2009) **27**, 667–681

Defects in offsite construction: timber module prefabrication

HELENA JOHNSSON* and JOHN HENRIK MEILING

Department of Civil, Mining and Environmental Engineering, Luleå University of Technology, Luleå, 97187 Sweden

Received 11 November 2008; accepted 28 April 2009

The construction industry is based on craftsmanship. Quality control and assurance procedures applied in manufacturing cannot usually be readily applied in construction, where there are higher degrees of uniqueness in each project. One category of companies, industrialized housebuilders, is attempting to bridge some of the gaps between construction and manufacturing. These companies prefabricate building modules for later assembly at the building site. Since they are wholly responsible for large parts of the building process, these companies have greater opportunities to control and improve quality in a more consistent way than ordinary construction companies. Thus, it could be hypothesized that the frequency and severity of defects should be lower in industrialized housing than in ordinary construction. The aim of the study presented here is to examine this hypothesis by measuring and characterizing defects in industrialized housing. The design and manufacturing processes at two Swedish timber module prefabrication firms has been analysed through interviews, site visits and document reviews. Quality audits from three phases of the building process were compiled, analysed and categorized to provide statistical measures of defects in industrialized housing. The results show that the case study companies are better in terms of product quality than conventional housing.

Keywords: Building defects, offsite production, quality management, industrialized housing, modular construction.

Introduction

Both governmental and customer demands for enhanced product quality and lower product and production cost in construction make it interesting to investigate how reduction of defects can contribute to enhanced product quality. From a lean production perspective, defects and rework are waste (Liker, 2004). The cost of poor quality is proven to be greater than the investment for managing quality (Juran and Gryna, 1988; Sörqvist, 1998) and should be eliminated by e.g. learning from experience (Wilson *et al*., 1993). When focusing on quality and product effectiveness an adequate definition regarding construction is 'fitness for use' (Juran and Gryna, 1988), i.e. quality is determined by the customer. Bisgaard (2007) suggested two subsidiary definitions: (1) quality of design; and (2) quality of conformance. This paper concerns the latter, i.e. identifying the mixture of random and chronic problems related to both internal and external customers (Bergman and Klefsjö, 2003). Reducing deviations and removing their causes is the essence of continuous improvements. According to Juran (1986) any production is charged with a current level of chronic waste, to be regarded as the level of opportunity for improvement. The Juran trilogy of planning, control and improvements constitutes a threefold strategy for enhanced quality (Figure 1).

Offsite construction is thought to have the potential to increase efficiency and control, reduce costs and increase quality in construction (SOU, 2000; Roy *et al*., 2003; Apleberger *et al*., 2007). Industrialization in construction is not a new phenomenon (CIB, 1965), and the emerging industrialization follows an international trend; e.g. Egan (1998) argues that construction must develop into a manufacturing process. The choice of manufacturing offsite does not in itself lead to effectiveness and efficiency (Gibb, 2001). Lessing *et al.* (2005) raise systematic performance measurement and use of knowledge acquired through experience as a key ingredient for industrialized housing. Offsite manufacturing of timber-framed modules is one application of offsite modern methods of construction (Buildoffsite, 2006; Pan *et al*., 2007). The use of modules shifts 90%

*Author for correspondence. E-mail: helena.johnsson@ltu.se

Construction Management and Economics
ISSN 0144-6193 print/ISSN 1466-433X online © 2009 Taylor & Francis
http://www.informaworld.com
DOI: 10.1080/01446190903002797

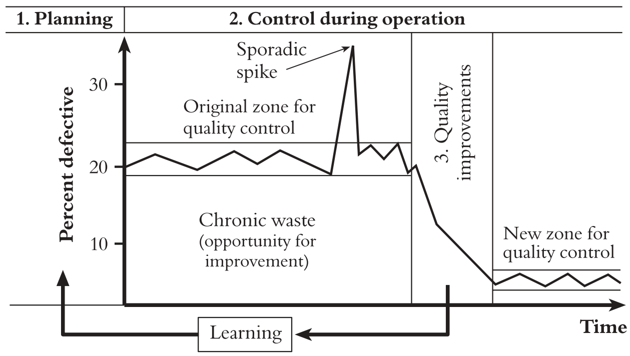

Figure 1 The Juran trilogy (developed from Juran, 1986)

of the work from the site into factories, Figure 2. Höök (2006) states that this kind of industrialized housing changes the company culture from organizational learning and learning between projects, to building process knowledge.

Early defect studies, e.g. Schodec (1982), Kaplin (1994), often focused on poor craftsmanship and negligence (Pheng and Wee, 2001). While Ramly *et al.* (2006) focus on design implications for defect occurrence, engineering-based defects are supported by quality management systems such as ISO 9000 (Low and Teo, 2004). Several studies (Josephson and Hammarlund, 1999; Porteous, 1992) have also linked the occurrence of defects to the organization and, more specifically, poor communication. Thus, organizational learning (e.g. Senge, 2006) may be a key ingredient for successful application of quality management procedures as described by Scott and Harris (1998). Ilozor *et al.* (2004) argue that historical analysis can be a powerful tool, which can be combined with categorization and systemization of defects (Josephson and Saukkoriipi, 2007). Estimates suggest that costs for correcting defects may account for up to 6% of the production costs (Josephson and Hammarlund, 1999). Industrialized housing production shares scheduling problems with regular construction, though it has the advantage of a dry working environment and above all traceable defects in production and design. Offsite manufacturing could be assumed to be of generally higher quality than construction by conventional methods (Pan *et al.*, 2008), but the level of chronic waste has not been established. This study focuses on defects and anomalies recorded in quality audits of work done by two offsite manufacturing housebuilders that produce timber-framed modules for the Swedish market. The aim of this study is to characterize defects and present the production process at two companies (Table 1) in order to establish knowledge on the current quality level.

Each of the two companies has 50 years' production experience and together they account for 50% of the market for modular housing in Sweden, which in turn has a 15% share of the total market for multi-family dwellings and commercial buildings. Clients in this segment are mostly real estate trustees and municipalities, i.e. professional clients who conduct repeated procurement under more severe functional requirements (regarding fire, sound and capacity) than those of single family dwellings. However, the building code is the same regardless of material and production in Sweden.

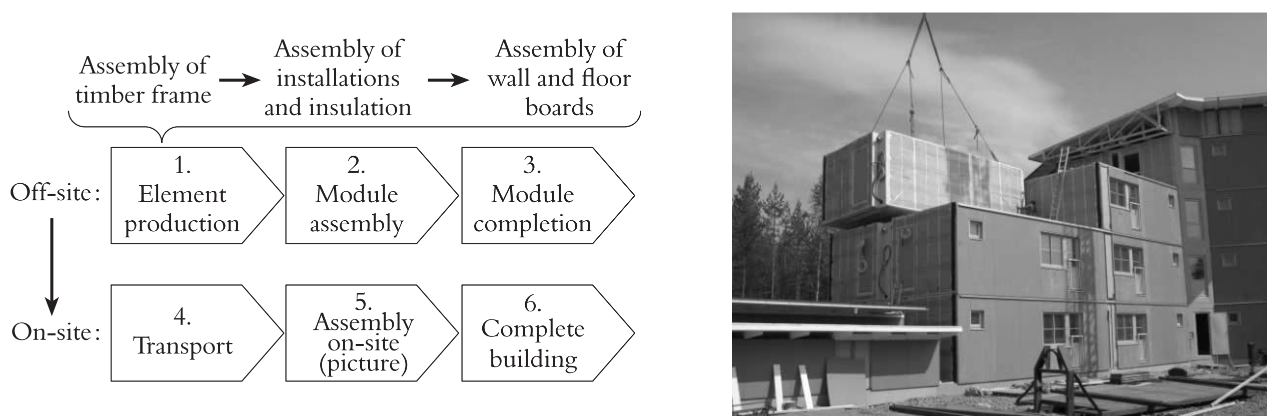

Figure 2 Timber module production and assembly

Table 1 Characteristics of studied industrialized housebuilders

Case company	No. of employees	Main products	Turnover (€m)	No. of storeys	Annual production (modules)	Contract type
A	150	Multi-family and student dwellings	34	Mainly 4–5	1400	Design build
B	253	Nursing homes, schools, office buildings	43	Mainly 1–2	1500	General

Timber module prefabrication

The two investigated companies are 1100 km apart and work with different clients. Still there are substantial similarities in the production process. The organization is not process-oriented in any formal way but projects follow predefined paths involving multiple activities (Figure 3). Most activities remain in-house, although some are performed by external consultants, i.e. drafting of heating, ventilation and air conditioning (HVAC), and electricity as well as structural design. Company A works solely for clients who sublet dwellings to private customers, while company B works with institutions procuring public buildings, e.g. schools, jails, day-care centres etc. Company A has chosen to work with its clients very early in the building process, sometimes even before building permits are granted. Company B does not have this option since public buildings are subject to European procurement rules and thus have to be announced and open to competition. Early design decisions favouring industrialized housing are almost impossible to make in open bidding. Both companies preferably apply a make-to-order (Winch, 2003) production strategy, where company solutions can be readily applied and configured according to the client's wish. Company B is often pushed to accept design-to-order projects, where more extensive engineering is required, as they enter procurement later. Winch (2003) argues that traditional housing projects are based on the concept-to-order strategy, which does not favour module prefabrication where repetition is sought.

Briefing

Briefing, handled by the sales department (two persons at each company), includes four weeks of early client contacts, twelve weeks to acquire the building permit (only company B), eight weeks to prepare a tender and twelve weeks for tender negotiations and acceptance. The architectural work is conducted by either in-house or external architects who are experienced with the module prefabrication system. After briefing, a start-up meeting is held in which object-specific demands are considered. Early design work at company A is prioritized and assigned to a skilled senior design employee allocated to the sales department.

The design process

Both companies try to define standard joints, standard stairwells, standard wall and floor sections, etc. Since the layout of the building greatly affects its manufacturability, strategic alliances with architects and customers are sought to streamline the design process. Drafting of the building envelope is handled by the companies themselves, while HVAC drafting, structural design, electrical drafting and life-cycle costing are done by external consultants to varying extents. The building envelope is first developed and divided into modules suitable for manufacturing, and then follows detailed design in which the plane elements (walls, floors, etc.) are drafted. Standard CAD software for construction is used to produce drawings, a bill of materials is then generated from quantities taken directly from the drawings, and used as a basis for manually ordering the required materials.

The manufacturing process

Companies A and B produce 1500 and 1400 modules per year respectively, resulting in 8 to 10 each day. Once the structure of a module is complete in the factory, internal cladding, painting and decoration begin. The

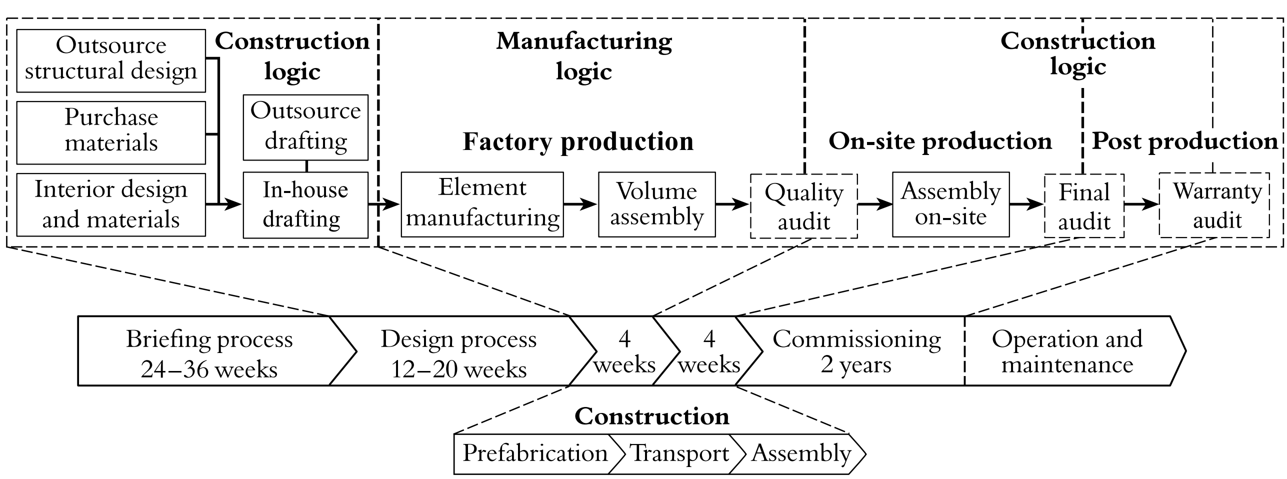

Figure 3 Timeframe for a typical building project and activities during design, manufacturing and commissioning stages

workers use printed drawings to keep track of work tasks for a particular module. Before covering and storing the module, deviations are reported and all missing equipment or incomplete work is noted. Notations are used for ordering material or assigning labour to correct defects. No one is assigned responsibility for improving activities or product development, and there are as yet no formal procedures for fostering such improvements.

Onsite assembly

Modules are transported by truck and managed on site by small groups, five people in each, of in-house teams (company A) or external carpenters (company B). The teams have inherent knowledge about practical aspects of the building system. At the building site information about work activities, equipment and construction material is channelled through ad hoc meetings and brief instructions on an irregular basis. Common problems are e.g. keeping track of material that has been sent inside the modules from the factory, and the lack of detailed work standards for specific tasks. Thus all teams have their own solutions concerning matters such as edging, joints and doors.

Research method

The results and conclusions reported here are drawn from two companies, representing a niche in offsite manufacturing; 17 housing projects were investigated. These housing projects are considered as 'one-of-a-kind' on a system level, but the companies aim to handle unique projects in repetitive processes. Defects are detected at several control points in the building process (Figure 3). In Sweden there is one mandatory audit (final audit) when a building is complete and a second mandatory audit (warranty audit) after the building has been in service for two years, both conducted by certified professionals (Figure 4). Certification (given by SP SITAC, an approval and certification body) is given to individuals after a minimum of five years' skilled experience in the construction field and 300 hours' experience in auditing. Building and warranty audits are formalized and sustained through an association of clients, consultants and contractors in the Swedish construction trade. The sets of rules are presented in general regulations for construction, AB (2004) and design-build contracts, ABT (1994). In addition, the studied companies make an internal quality audit (factory audit) before the modules leave the factory (Figure 4).

The analysis was restricted to eight projects run by companies A and B for which complete data were available (factory, final and warranty audits, Table 2).

In addition a set of 11 projects (regarding final audits from company A, Table 3) was used to validate the results.

In total, 1320 (443 + 877) modules were included in the analysis of quality audits. Across the eight projects

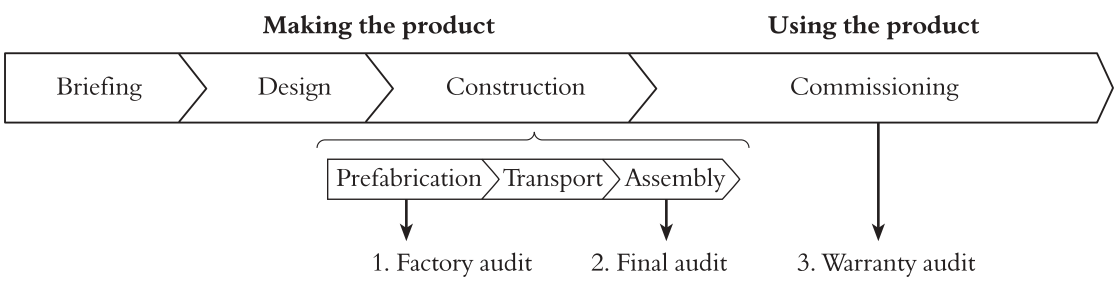

Figure 4 The three audits in relation to the building process

Table 2 The eight selected projects where factory audit, final audit and warranty audit were investigated

Case company	Selected projects (no. of modules)	No. of storeys	Year
A	Condominiums (40 mod.)	2	2004
	Student dwellings (92 mod.)	4	2003
	Student dwellings (230 mod.)	4	2003
B	School (11 mod.)	1	2006
	Hospice (19 mod.)	1	2005
	Preschool (16 mod.)	1	2005
	Preschool (28 mod.)	1	2005
	Preschool (7 mod.)	1	2005

Table 3 The eleven selected projects where only final audits in company A were summoned

Case company	Selected projects (no. of modules)	No. of storeys	Year
A	Condominiums (48 mod.)	2	2004
	Condominiums (172 mod.)	4	2003
	Condominiums (82 mod.)	4	2003
	Condominiums (174 mod.)	4	2006
	Student dwellings (54 mod.)	4	2005
	Student dwellings (92 mod.)	4	2003
	Condominiums (64 mod.)	2	2005
	Condominiums (36 mod.)	4	2007
	Condominiums (67 mod.)	4	2007
	Student dwellings (60 mod.)	4	2006
	Rental apartment (28 mod.)	2	2007

Table 4 Nominal scales for characterizing defects

Where did the defect occur?	What was defective?	What type of defect was it?	What measures were taken to correct the defect?	Why did the defect occur (root cause)?	When did the defect occur?
0 Unrelated	0 Unrelated	0 Unrelated	0 Unrelated	0 Unrelated	0 Unrelated
1 Dwelling	1 Int. installations	1 Missing	1 None	1 Transport	1 Structural design
2 Common areas	2 HVAC	2 Unfinished	2 Cleaning	2 Damaged	2 Factory
3 Separate buildings	3 Opening	3 Broken	3 Adjustment	3 Bad craftsmanship	3 Transport
4 Outdoors	4 Lining	4 Erroneous	4 Completion	4 Structural error	4 Assembly
	5 Wall		5 Repair		5 Warranty time
	6 Ceiling		6 Exchange		
	7 Floor				
	8 Completions				
	9 Information				

in Table 2, 1234 defects were detailed in the factory audits, 1147 in the final audits and 332 in the warranty audits; the final audit from the 11 projects in Table 3 constitutes 2415 defects giving a grand total of 5128. Defects are recorded (by inspectors) as text documents and at the best stored in the companies' archives. The summoned documents were reviewed and all defects coded using six different categories: where, what, type, measure, why and when. Each category was associated with a nominal scale according to Table 4, corresponding partly to Love and Josephson (2004), who categorized defects according to classification, correction, roots and cost effects.

The first two categories (where and when) were each divided into more detailed sub-categories (Tables 5 and 6). Every defect was coded and entered in SPSS statistical software for analysis and presentation of data in a consistent manner.

Table 7 exemplifies a handful of coded defects from the final audits. Tables 4 to 6 provide the code key; the first pair of digits (2–7) is 'Where' in Table 4 with the sub-category from Table 5, the second pair (3–2) is 'What' in Table 4 with the sub-category from Table 6. The following four single digits are 'Type', 'Measures', 'Why' and 'When' in Table 4.

A series of three focus group meetings was held in order to attain feedback from the investigated companies on the defect analysis. Three onsite visits have

Table 5 Sub-categories for the 'Where' category in Table 4

Where	Where
2 Common areas	3 Separate buildings
1 Waste disposal	1 Waste disposal
2 Laundry	2 Laundry
3 Storage room	3 Storage room
4 Ventilation	
5 Electricity	
6 Cleaning	
7 Entrance	
8 Stairwell	
9 Corridor	

Table 6 Sub-categories for the 'What' category in Table 4

What	What	What	What	What	What
1 Int. installations	2 HVAC	3 Opening	5 Wall	7 Floor	8 Completions
1 Kitchen	1 Radiator	1 Windows	1 Tiles	1 Clinker	1 Balcony
2 Bathroom	2 Pipes	2 Doors	2 Wallpaper	2 Carpet	2 Oriel
3 Room	3 Electricity	3 Openings	3 Painting	3 Parquet	
		4 Linings			
		5 Threshold			

Table 7 Examples of coded defects from final audits

Deviation notation	Code
Paint defect on entrance door	(2–7) (3–2) 4 3 3 4
Crack in the roof	(1–0) (8–1) 3 6 2 4
Deviating colour on carpet	(1–0) (1–1) 4 1 4 1
Window needs adjusting	(2–0) (3–1) 4 3 1 3
Entrance door hitting radiator	(2–9) (3–2) 4 1 4 1

Note: See Tables 4 to 6 for code key.

been conducted in order to participate during audit performance and to trace root causes.

Results and analysis

On average from the eight projects in Table 1, each module had 6.1 (2713/443) defects (accumulated from all three audits). Defects were distributed in the three control points accordingly: (1) factory audit had 2.7 (1234/443) defects per volume; (2) final audit had 2.5 (1147/443) defects per module; and (3) warranty audit had 0.7 (332/443) defects per module. Modules made by companies A and B had, on average, 5.0 and 9.3 defects per module, respectively. Company A produces dwellings, which are not official buildings and are not subject to the European Procurement Agreement, which is the case for company B that has more site work (generating more defects) because of more extensive technical installations in HVAC and electricity.

When analysing final audits from the 11 projects in Table 3 the amount of defects per module is 2.7 (2415/877) and defects per habitat is 5.3 (2415/453). Sigfrid (2007) investigated building inspections (final audits) from six traditionally built projects and found 9.3 defects per habitat in three projects containing 91 multi-storey habitats, and 16.2 defects per habitat in three projects containing 73 terraced houses. The grand average being 12.7 defects per habitat, the case study companies produce 42% of this amount of defects. It can be hypothesized that the difference lies in the part of the process that is industrialized, thus if the investment ratio is 2:1 regarding prefabrication and onsite production, prefabrication should compare only 2/3 of its defects to onsite production. This leads to a speculation that offsite production in the case study companies instead generate 32% (10.9/3.5) defects in the final audits compared to onsite projects.

Where did the defects occur?

This question is linked to how far the building process has progressed at the time of the audit. Total numbers of defects in separate buildings, outdoors, common areas and dwellings recorded in each class of audit are presented in Figure 5.

Dwellings harness the most defects, which is not surprising since they constitute the major parts of the buildings. The higher proportion of defects in common areas recorded in the final audits (which can be seen in Figure 5) is also no surprise since common areas are constructed during onsite work, and thus their frequency will inevitably rise in the final audits.

What was defective?

The generic parts of the building structure were used to map the defects (Figure 6). Recorded defects include holes and mess on the walls caused by craftsmen, missing linings around doors and windows, and doors in need for adjustment owing to movements in the structure. Of the grand total, 33% of all defects were related to walls, and 52% to walls or openings. The contractor is held responsible for defects in interior installations concerning objects that are missing or not properly installed. In the warranty audits malfunctions were noted. Sub-categories from the most prominent groups (60% of defects) from the factory audits (Figure 6(b), wall, opening and interior installations) are presented in a Pareto chart, Figure 6(d).

The Pareto chart in Figure 6(d) reveals what could be regarded as 'the vital few' (Juran and Gryna, 1988) identified here as windows and doors, which are the main causes of defects at both companies. Discussions in focus group meetings revealed that both windows and doors are expensive to purchase, as well as time critical for delivery (early order). The purchase

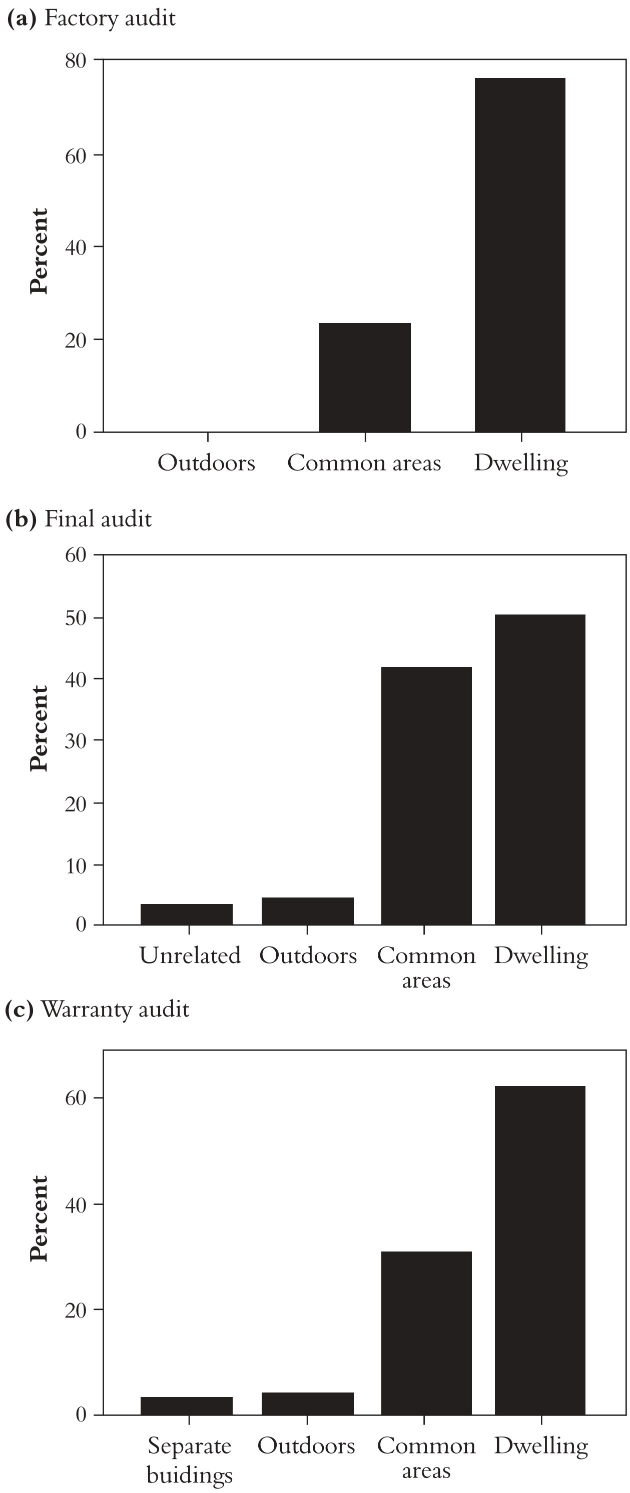

Figure 5 Where did defects occur?

department chose to buy non-adjustable doors and to mount windows without adjustment screws. This is a questionable decision as the modules move during transport and assembly, resulting in costly adjustments on site. A lean production implementation is underway in company A, implying a willingness to decrease the defect rate through improved communication and management support as supported by Josephson and Hammarlund (1999) and Porteous (1992). A lean strategy could eventually lead to a decrease of small defects, missing objects and faulty installations through standardization, continuous improvements and supply chain management. Company B is a 'fire fighter', relying on hard work as well as maintaining an ISO 9000 certificate, neither of which has proven to bear fruit regarding enhanced quality and lowered defect rate (Gustafsson *et al.*, 2001; Lam and Ng, 2005).

What type of defect was it?

The cost for correcting a defect is clearly coupled to the type of defect involved, therefore it is of obvious interest to grade the severities of the defects (as illustrated in Figure 7).

Figure 7 shows that many items went missing before module delivery (518 items in total, equivalent to 1.2 items missing per module, accounting for 42% of the defects recorded in the factory audits). Furthermore, many defects recorded in the factory audits concerned broken items (35%) that had to be corrected before the final audit. In the final audits, the lion's share of defects concerned things that were not delivered according to the contract (55%). On average, 79 items per project were listed as unsatisfactory in the final audit. According to the warranty audit, some 20 items per project did not meet contract stipulations. The final and warranty audits demonstrate that many defects are related to failure to fulfil customer demands regarding installations in the building (alarm systems, professional kitchen appliances, etc.). Thus, there is great potential for improvements in the companies' procedures for addressing these issues, which are not directly linked to the framing system, but are still part of the overall offer. Figure 7(d) shows defects recorded by Sigfrid (2007) on final audits from six traditionally built projects. Figure 7(d) indicates that the level of items not installed or delivered according to contract is far lower than in the case study companies, Figure 7(b). Here is a potential for the case study companies to synchronize the flow of information, material and construction workers (activities), as well as required resources in the factory and on site. From a lean supply chain management view all efforts should be made in order to avoid reoccurrence of defects or unsatisfactory matters (Stratton and Warburton, 2003) which coincides with Juran's (1986) view of chronic waste. The supply chain is handled through contracts and agreements but relations are not fully developed to handle the kind of line-balanced,

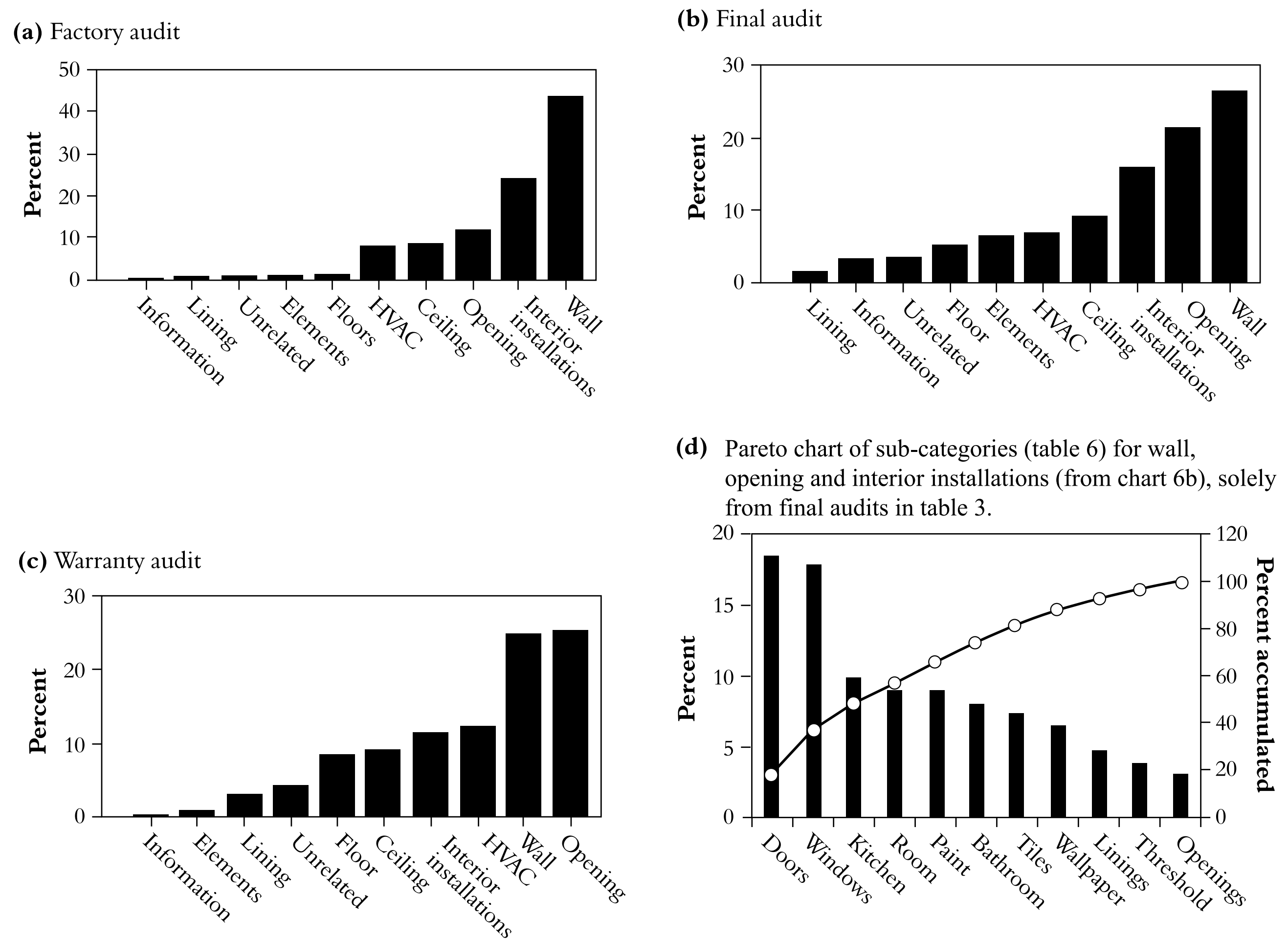

Figure 6 What was defective?

time-critical production that module production constitutes.

What measures were taken to correct the defects?

To qualitatively assess the costs for the defects and establish another measure of the costs for correcting them, the measures taken to correct each defect were recorded (Figure 8).

Most of the defects (51% of the total) were small, requiring only minor adjustments. Typical defects, getting much attention in audits, included stains, mess, small cracks and marks. It is shown by Höök and Stehn (2008) that the production culture in Swedish timber frame module production still relies on a traditional onsite culture resulting in low worker motivation, lack of continuous improvement, problems that appear being solved but not analysed, ad hoc solutions and a low responsibility for maintenance of equipment. Thus the level of defects could be expected to decrease if/when implementing tools such as 5S and standardized work as it improves the repetitive process, making mistakes easier to discover and improvements possible to measure. The numbers of defects requiring repair or exchange amounted to 9.6% (260/2713) of the total. In the factory audits completion was the second most common measure to correct defects, which is unsurprising since many items were missing in that phase.

Why did the defect occur?

In accordance with expectations, a work-intensive activity such as construction results in many defects originating from human errors, both from factory production and assembly on site (Figure 9). One of the major criticisms that has been raised against timber module prefabrication (Höök, 2006) concerns the choice of building system (lightweight timber frame walls and floors assembled into modules). One would therefore expect a substantial frequency of defects to be associated with the building system or structural design and, accordingly, 21% (578/2713), here implied to constitute the vital few (Juran, 1986), of the grand total of recorded defects can be directly linked to the

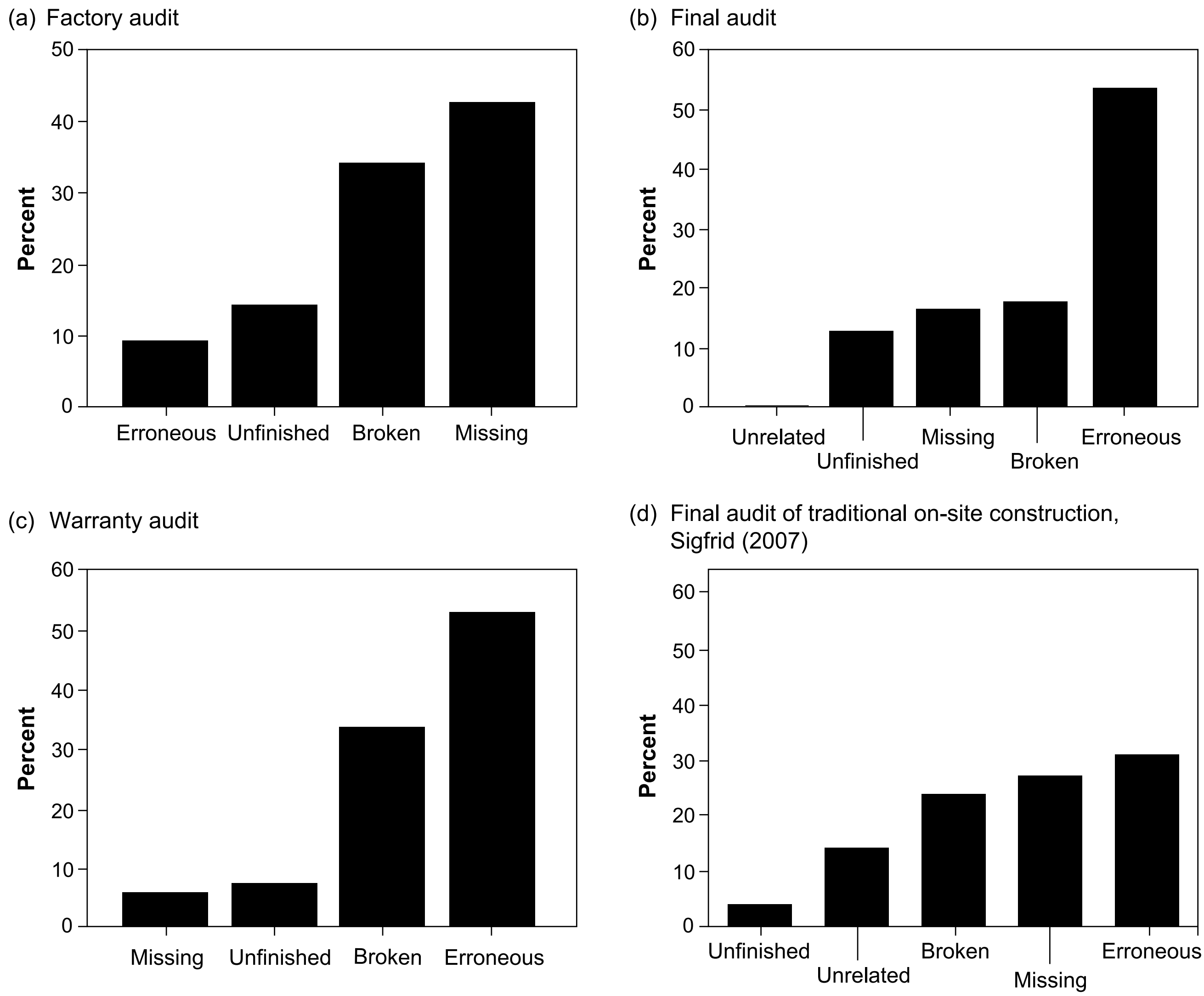

Figure 7 Types of defects

structural design phase and/or building system. Structural errors constituted nearly half of all the defects listed in the warranty audits, corresponding to 6% of the grand total including cracks in corners and movements in the structure. Defects are of several types: as *chronic waste* visible in audits as cracks in weak sections and as *design errors* such as misplacement of doors or poor choices of material. The standard procedure to correct these cracks is to use putty and paint. Yet another crack type was encountered at company A and could be defined as lack of standardized work in the factory resulting in prominent cracks (Figure 10). The cracks propagated during the two lifts during production, one with a fork truck in the factory and one with a crane at the construction site.

Walls were dismounted revealing that studs and plywood were not mounted according to instructions. The root cause is lack of standardized work, and it is to be considered as a sporadic production spike (Figure 1) and should not be confused with quality improvement measures. In general the building system requires some modification to improve long-term performance and responses to settlement. The overall performance is satisfactory, but not excellent.

When did the defect occur?

Transport and lifts cause some 10% of the defects detected in the final audits (Figure 11) manifested in cracks in weak sections, and windows and doors in need of adjustment. Half of the defects detected in the warranty audits arose during the two years that had passed since the final audits. However, even after two years, defects either remained or had arisen that can be directly linked to errors during the factory production (20%) or building assembly (23%). Almost half of the

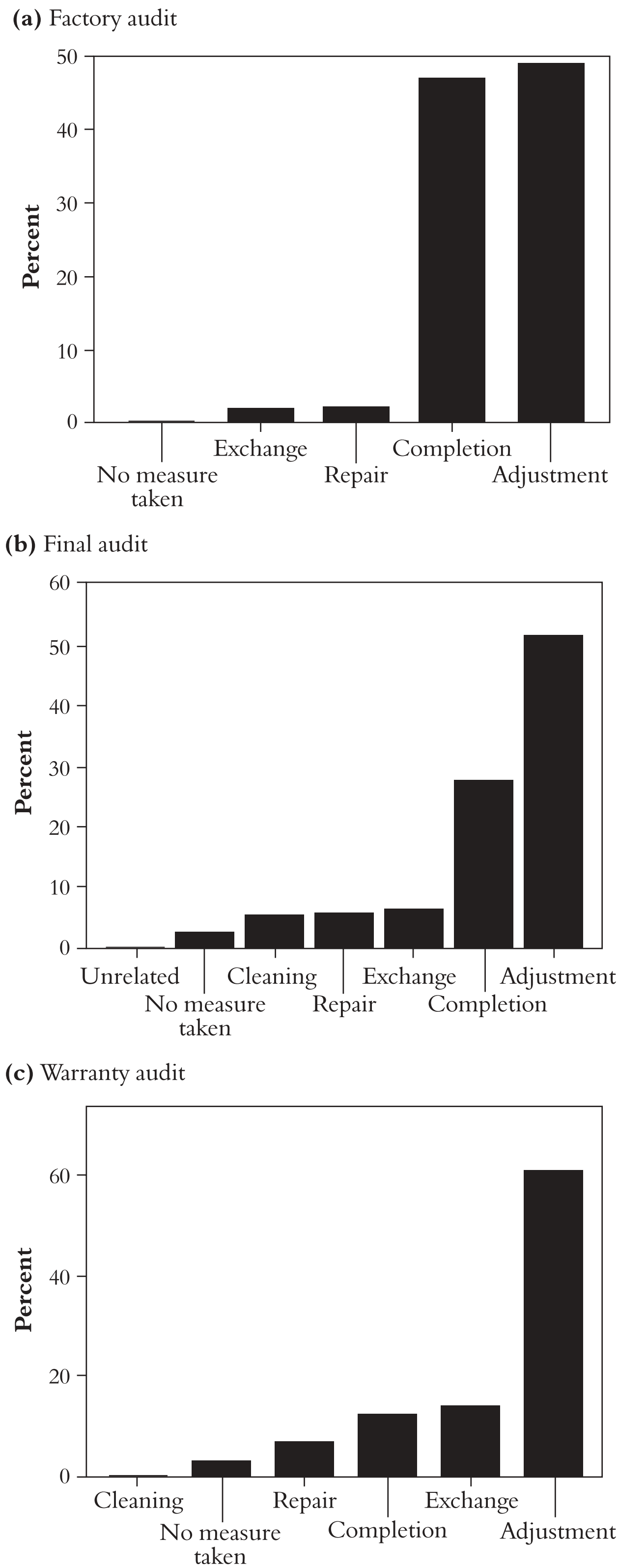

Figure 8 Measures taken to correct defects

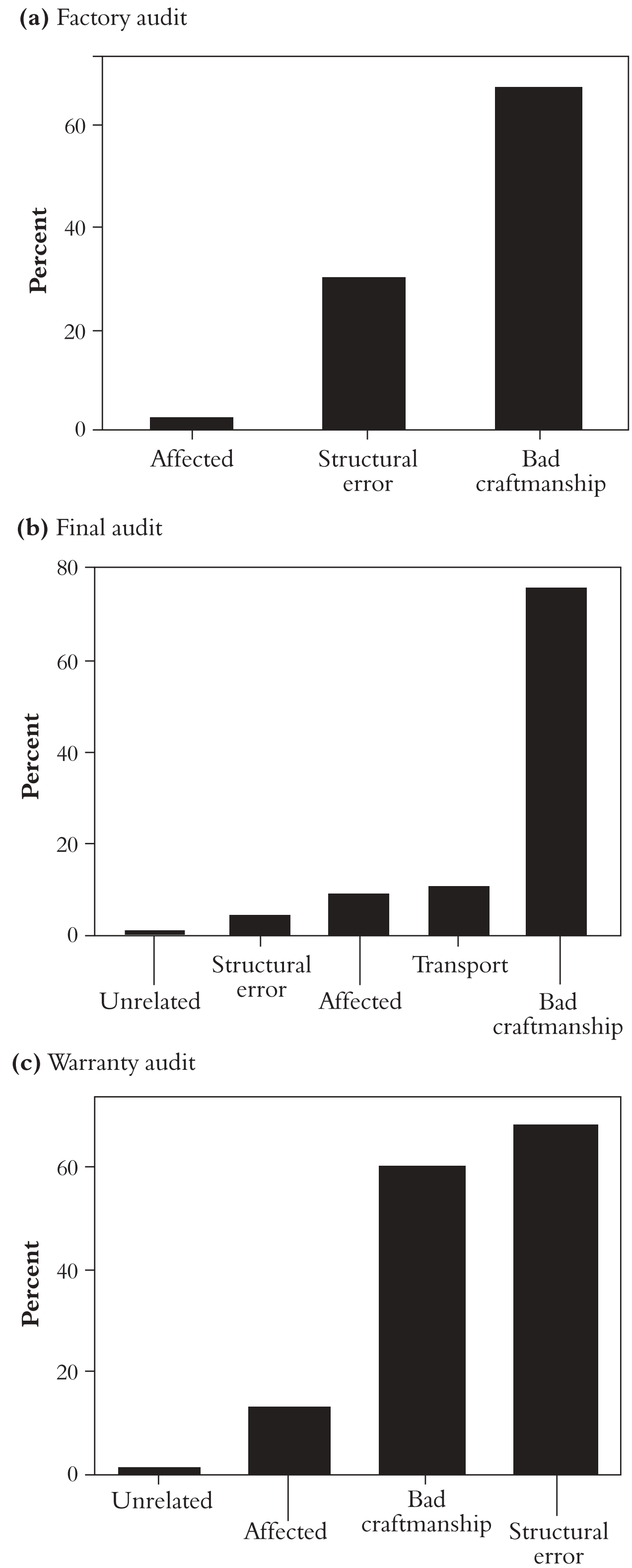

Figure 9 Root causes of defects

Figure 10 Cracks propagating from door openings, after lift

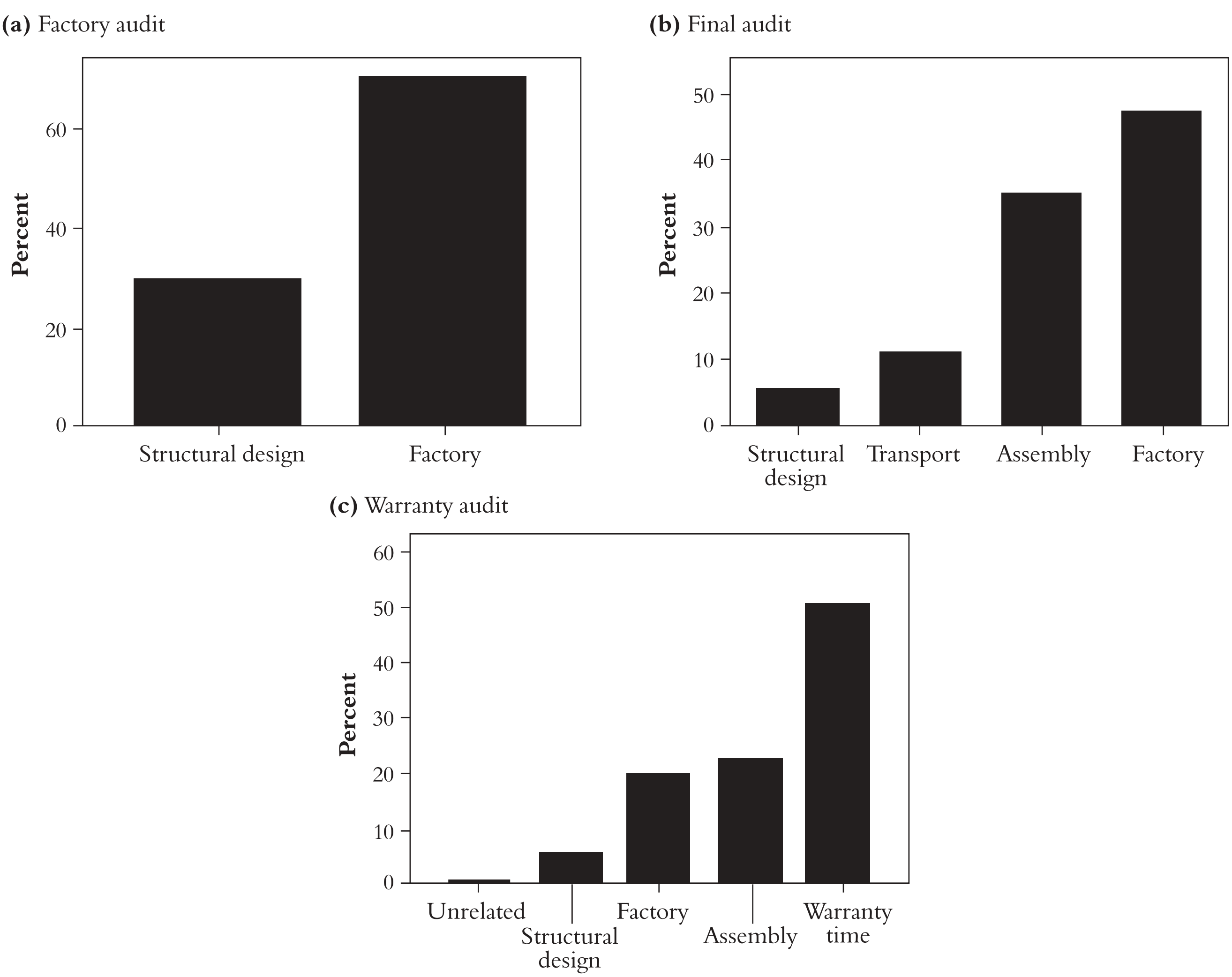

Figure 11 Building process stage when defects occurred

defects recorded in the investigated final audits originated from factory production, followed by 35% from assembly activities. Production in the factory is intense, and this is where attempts to optimize the work have primarily been focused. But factory production of housing projects is saddled with high process variability as the projects so far tend to be one-of-a-kind on a system level. As factory production is managed through specialized craftsmen in both companies, it could be described as moving onsite construction indoors and not adjusting to factory physics. A line-based production would level the flow and even out variations in tact time (Hopp and Spearman, 2001). Relatively little attention has been paid to the assembly phase, but this should be worthwhile, especially for company B, since many defects pertain to installations handled in the assembly phase.

Principal component analysis

Datasets in the factory, final and warranty audits were each subjected to principal component analysis (PCA). There was insufficient scatter in the factory audit data to summarize into aggregated variables, which is not surprising since several of the scales applied only allow one or two categories at the factory audit stage, e.g. 'where' can only elicit the responses '0, Unrelated' or '1, Dwelling' since the other alternatives in the scale are non-existent at the time of the factory audit. Rotated component matrices for the PCAs of the final and warranty audits are presented in Table 8.

The PCAs show some relationships that remained consistent throughout the timeframe of the quality audits. The first principal component (PC) obtained from the PCA of the final audits is designated 'Matter_3D', and describes what was defective in combination with the positions of the defects. Accordingly, the final audits show that it is not uncommon for certain types of defects to repeatedly occur—for instance cracked corners may repeatedly occur at the same position for the same reasons. The first PC obtained from the PCA of the warranty audits, 'Position_4D', also has positional contributors, but in this case it is also related to time, which is consistent with expectations since time can only be related to defects at specific positions after some time has elapsed. Defects typically detected in the warranty audits include cracks around openings as a result of settlement. This type of defect can only be detected during the warranty period, since it is invisible before it. One component that arose in both analyses illustrated in Table 8 is 'Problem_fix', which combines the defect type with the measure to correct it. This component shows that the type of defect detected and the corrective measure are closely related and could be described using just one variable, which should facilitate future analysis. The connection is also unsurprising since small defects also need small measures for correction. Defects ultimately should be coded at source during inspection or as self-inspection in order to facilitate later analysis leading to enhanced possibility working and gaining from both historical analysis as well as categorization of defects (Ilozor *et al.*, 2004; Josephson and Saukkoriipi, 2007). To assess possible differences between companies A and B in terms of defect-related variables, scatterplots were produced, but none of them indicated any significant differences between the companies (Figure 12). No statistically significant differences between them in these respects were detected by a t-test either.

From Figure 12 it is evident that the scatter around zero is evenly distributed for both companies and there is no significant clustering of data or interesting outliers that requires attention.

Table 8 Component matrices (rotated by Varimax with Kaiser normalization) for the principal component analyses of the final and warranty audits

(a) Final audit

	Component		
	Matter_3D	Problem_fix	Time_cause
Where_1	0.78		
What_1	−0.65		
Where_2	0.54		
Measures		0.84	
Type		−0.77	
When			−0.83
Why			0.71

(b) Warranty audit

	Component		
	Position_4D	Matter_cause	Problem_fix
When	−0.71		
Where_2	0.69		
Where_1	0.58		
Why		0.77	
What_1		0.76	
Type			−0.76
Measures			0.70

Discussion and conclusions

The defect information presented in this paper is extracted from existing quality documents, representing

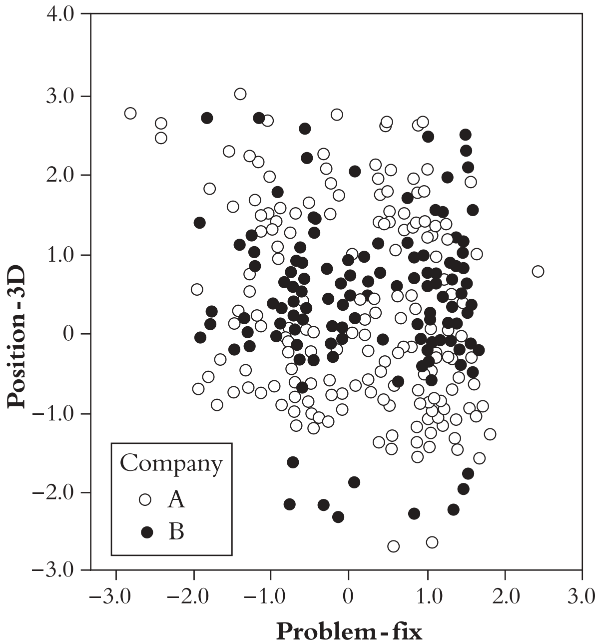

Figure 12 Example of scatterplot from the PCA of the final audits

a neglected source of information. As these data are currently readily available in mandatory audits it represents a low-hanging fruit. Why is it that the companies currently use audits only as checklists for correcting defects and make little use of information captured in the audits for further analysis? We believe this is due to several reasons. First there are no explicit demands from clients or authorities. Secondly there are cultural reasons (based on norms of traditional onsite and project-based construction), which influence the organizational culture of industrialized housing resulting in lack of standardization, lack of employee loyalty to strategies and a lack of top management support and strategies (Höök and Stehn, 2008). Working with identification of defects and deviations is here demonstrated to have potential to support improvements of process and product design, thus favouring both clients and company in the long run, rather than just getting one project approved and solely correcting finalized products in fire-fighting mode. The perceived benefits of industrialized housing cannot be achieved by focusing solely on external customer value, while suppressing internal production efficiency and forgetting internal customers. The struggle for quality in construction is a small step revolution where control of defects should be linked to an improvement strategy. It is shown that the case study companies achieve a lower defect rate in the final audits than the six compared onsite projects. Production in the case study companies is done in a closed factory environment, with assembly and some finishing performed at the construction site. The importance of being in control of the entire defect recovery process is demonstrated in this study and supported also by the findings of Love and Josephson (2004). From a learning perspective these companies could benefit more from applying organizational (company) learning (Kärnä and Junnonen, 2005) than conventional construction companies, since the individuals, teams, customers and relationships involved in their projects are more constant and controlled. Altogether, several key ingredients required for advancing and exploiting experience feedback and learning are present, which could provide a competitive edge with respect to other building systems and promote long-term quality.

However, methods need to be introduced to standardize experience capture and, more importantly, implement knowledge gained through experience in earlier process stages. This problem has been addressed in several studies, e.g. Shelbourn *et al.* (2006) and Sandberg *et al.* (2008), but no simple, robust way of tackling it has been implemented as of yet. If the development of product quality in the housing industry is to be conducted through the people working in a company, the defects signal a need for learning in the organization rather than a technical, economical problem. The main reasons for investigating defects are to lower poor quality costs and improve production efficiency, product quality and customer satisfaction. The case study companies have the potential to take full advantage of quality management, but they need to shift focus from project-based to process-based production (Winch, 2006).

This investigation focused on two industrialized housing companies and projects procured by repeat clients. If generalization towards offsite modern methods of construction, or industrialized housing or even modular building systems is sought, extended investigations would preferably include also European companies outside Sweden. Further research will focus on how deviations can be continuously gathered and cumulated, analysed, traced and corrected to support continuous improvements and process development. As one of the two investigated companies has just recently decided to apply a lean manufacturing approach further investigations should measure improvements regarding the occurrence and severity of defects. Further comparison regarding onsite and offsite production would take into consideration defects per square meter living or gross area and e.g. form of tenure. The comparison of onsite construction was made in respect of only six traditionally built projects; statistically this would benefit from a broader investigation and should be treated accordingly.

Acknowledgements

Financial support from the Swedish Governmental Agency for Innovation Systems, VINNOVA and the participating companies in the study, is gratefully acknowledged. This work was performed within the competence centre Lean Wood Engineering and with support from the SkeWood programme.

References

AB (2004) Allmänna bestämmelser för byggnads-, anläggnings- och installationsarbeten [General regulations regarding construction, in Swedish]. Byggandets Kontraktskommitté, Svensk byggtjänst, Solna, Sweden.

ABT (1994) Allmänna bestämmelser för totalentreprenader för byggnads-, anläggnings- och installationsarbeten [General regulations regarding design build contracts in construction, in Swedish]. Byggandets Kontraktskommitté, Svensk byggtjänst, Solna, Sweden.

Apleberger, L., Jonsson, R. and Åhman, P. (2007) *Byggandets industrialisering, nulägesbeskrivning* [The industrialization of construction, a current state report, in Swedish], Sveriges Byggindustrier, Gothenburg, Sweden.

Bergman, B. and Klefsjö, B. (2003) *Quality from Customer Needs to Customer Satisfaction,* Studentlitteratur, Lund, Sweden.

Bisgaard, S. (2007) Quality management and Juran's legacy. *Quality and Reliability Engineering International,* **23**, 665–77.

Buildoffsite (2006) Buildoffsite: glossary of terms, available at www.buildoffsite.com (accessed 10 March 2009).

CIB (1965) *Towards Industrialised Building, Proceedings of the Third CIB Congress,* Copenhagen, Denmark, Elsevier Publishing Company, Amsterdam.

Egan, J. (1998) *Rethinking Construction,* Construction Task Force Report for Department of the Environment, Transport and the Regions, HMSO, London.

Gibb, A.G.F. (2001) Standardisation and pre-assembly—distinguishing myth from reality using case study research. *Construction Management and Economics,* **19**(3), 307–15.

Gustafsson, R., Klefsjö, B., Berggren, E. and Granfors-Wellemets, U. (2001) Experiences from implementing ISO 9000 in small enterprises—a study of Swedish organisations. *The TQM Magazine,* **13**, 232–46.

Höök, M. (2006) Customer value in lean prefabrication of housing considering both construction and manufacturing, in *Proceedings of IGLC 14,* Santiago, Chile, 25–27 July, pp. 583–94.

Höök, M., and Stehn, L. (2008) Lean principles in industrialized housing production: the need for a cultural change. *Lean Construction Journal,* 20–33.

Hopp, W. and Spearman, M. (2001) *Factory Physics: Foundations of Manufacturing Management,* 2nd edn, McGraw-Hill, New York.

Ilozor, B.D., Okoroh, M.I., Egbu, C.E. and Archicentre (2004) Understanding residential house defects in Australia from the State of Victoria. *Building and Environment,* **39**, 327–37.

Josephson, P.-E. and Hammarlund, Y. (1999) The causes and costs of defects in construction: a study of seven building projects. *Automation in Construction,* **8**, 681–7.

Josephson, P.-E. and Saukkoriipi, L. (2007) Waste in construction: call for a new approach. Chalmers University of Technology. Report, The Centre for Management of Built Environment, Gothenburg, Sweden.

Juran, J.M. (1986) The quality trilogy: a universal approach to managing for quality. *Quality Progress,* **19**(8), 19–24.

Juran, J.M. and Gryna, F.M. (1988) *Juran's Quality Control Handbook,* McGraw-Hill, New York.

Kaplan, S.D. (1994) How we can reduce the incidence of defects in buildings, in *Proceedings of the International Symposium on Dealing with Defects in Building,* Varena, pp. 811–19.

Kärnä, S. and Junnonen, J.-M. (2005) Project feedback as a tool for learning, in *Proceedings of IGLC 13,* Sydney, Australia, 18–21 July, pp. 47–55.

Lam, K.C. and Ng, S.T. (2005) A cooperative internet-facilitated quality management environment for construction. *Automation in Construction,* **15**, 1–11.

Lessing, J., Stehn, L. and Ekholm, A. (2005) Industrialised housing: definition and categorization of the concept, in *Proceedings of IGLC-13,* Sydney, Australia, 18–21 July, pp. 471–80.

Liker, J. (2004) *The Toyota Way: 14 Management Principles,* McGraw-Hill, New York.

Love, P.E.D. and Josephson, P.-E. (2004) Role of error-recovery process in project. *Journal of Management in Engineering,* **20**, 70–9.

Low, S.P. and Teo, J.A. (2004) Implementing total quality management in construction firms. *Journal of Management in Engineering,* **20**, 8–15.

Pan, W., Gibb, A.G.F. and Dainty, A.R.J. (2007) Perspectives of UK housebuilders on the use of offsite modern methods of construction. *Construction Management and Economics,* **25**, 183–94.

Pan, W., Gibb, A.G.F. and Sellars, A.B. (2008) Maintenance cost implications of utilizing bathroom modules manufactured off-site. *Construction Management and Economics,* **26**, 1067–77.

Pheng, L.S. and Wee, D. (2001) Improving maintenance and reducing building defects through ISO 9000. *Journal of Quality in Maintenance Engineering,* **7**, 6–24.

Porteous, W.A. (1992) Classifying building failure by cause. *Building Research & Information,* **20**, 350–6.

Ramly, A., Ahmad, N.A. and Ishak, N.H. (2006) The effects of design on the maintenance of public housing buildings in Malaysia. *ABE International Building Engineer,* April, 30–3.

Roy, R., Brown, J. and Gaze, C. (2003) Re-engineering the construction process in the speculative house-building sector. *Construction Management and Economics,* **21**, 137–46.

Sandberg, M., Johnsson, H. and Larsson, T. (2008) Knowledge-based engineering in construction: the prefabricated timber housing case. *Journal of Information Technology in Construction (ITCon),* **13**, 408–20.

Schodec, D.L. (1982) Defects in public building construction. *Issues in Engineering Journal of Professional Activities,* **108**(4), 263–70.

Scott, S. and Harris, R. (1998) A methodology for generating feedback in the construction industry. *The Learning Organization,* **5**, 121–7.

Senge, P.M. (2006) *The Fifth Discipline: The Art and Practice of the Learning Organization,* Random House Business, London.

Shelbourn, M.A., Bouchlaghem, D.M., Anumba, C.J., Carillo, P.M., Khalfan, M.M.K. and Glass, J. (2006) Managing knowledge in the context of sustainable construction. *Journal of Information Technology in Construction (ITcon),* **11**, 57–71.

Sigfrid, L. (2007) *Fel och brister i nya bostäder—vad kostar det egentligen?* [Faults and mistakes in new dwellings—how much does it really cost?, in Swedish], Boverket, Karlskrona, Sweden.

Sörqvist, L. (1998) Poor quality costing, Doctoral thesis, Royal Institute of Technology, Department of Material Processing, Production Engineering. Stockholm, Sweden.

SOU (2000) Från byggsekt till byggsektor [From construction sect to construction sector, in Swedish], SOU 2000:44, Byggkostnadsdelegationen, Stockholm, Sweden.

Stratton, R. and Warburton, R.D.H. (2003) The strategic integration of agile and lean supply. *International Journal of Production Economics,* **85**, 183–98.

Wilson, P.F., Dell, L.D. and Andersson, G.F. (1993) *Root Cause Analysis: A Tool for Total Quality Management,* ASQC, Milwaukee, WI.

Winch, G. (2003) Models of manufacturing and the construction process: the genesis of re-engineering construction. *Building Research & Information,* **31**(2), 107–18.

Winch, G. (2006) Towards a theory of construction as production by projects. *Building Research & Information,* **34**, 164–74.