POTENTIAL OF POKA-YOKE DEVICES TO REDUCE VARIABILITY IN CONSTRUCTION

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ABSTRACT

This paper discusses the application poka-yoke devices to reduce variability in construction sites. Initially it presents the main pressures for improving production practices in the sector and then it describes the main aspects of reduction of variability. Subsequently, it presents poka-yoke as one of the basic heuristic approaches to implement this principle in practice.

The researchers investigated the application of poka-yoke in construction through six case studies carried out in Brazil and England. The pattern-matching approach, supported by quantitative and qualitative data, has confirmed the usefulness of this approach in construction practice. However, the empirical evidences revealed that the sector makes little use of this approach at the present moment. In this sense, there is great scope for developing mechanic and electronic mistake-proof devices to adapt into existing construction machinery. Construction suppliers should reflect on the idea of building poka-yoke devices in their products in order to guarantee the correct use of their products on site.

KEY WORDS

Poka-yoke, mistake-proofing, reduction of variability.

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BACKGROUND

Poka-yoke is among the fundamental heuristic approaches used by the most competitive production systems world-wide but still seems to receive little attention by practitioners and researchers in the construction sector. Indeed, at the present moment there is little research and publications on this topic in the construction management field. In this context, this paper intends to assess the current state of this approach in the sector and bring insights for innovations in industry and developments of future research. The study comes in an environment where construction suffers heavy pressure to improve its practices since it has to compete for investments with other increasingly sophisticated and competitive industries. Next section presents some of the most important pressures for change.

"There are no mistakes, no coincidences. All events are blessings given to us to learn from."
Elizabeth Kubler-Ross

PRESSURES FOR IMPROVE CONSTRUCTION PRACTICES

LOW PRODUCTIVITY

The construction sector usually represents a significant part of the Gross Domestic Product (GDP) and employment in most countries. In the UK, for example, the construction industry has averaged 7.5% of the GDP between 1992 and 1996, employing around 1.4 million people in 1998 (Office of National Statistics 1997, Egan 1998). Despite its great economic importance, the construction industry regularly presents lower levels of productivity when compared with the manufacturing industry. Indeed, in the USA it is reported that between 1970 and 1995 the productivity of the sector had decreased at a rate of –1.3% per year whilst in the same period the manufacturing industry increased + 3.5% per year (Teicholz 1997).

SOCIAL DEMANDS

The pressures for increase the productivity and added value in construction is high both in the Third World as well as in the developed nations. In Brazil, for instance, the housing deficit is estimate in 5.2 million and, adding to the problem, just a small fraction of these population is able to afford current housing costs (Picchi 1993). Changes in the population profile as much as their lifestyle is also bringing new demands to construction world-wide, mainly concerning modernisation, repair and maintenance works (Key Note 1997, VTT 1997).

HIGH LEVELS OF WASTE OF MATERIAL AND TIME

Levels of waste remain high in the sector despite economic and social pressures. Various studies have confirmed this argument by showing repetitively high levels of unproductive time in construction sites: 24% on average in Australia, Sweden, UK and Netherlands (Vershuren 1980), 43% in Nigeria (Olomolaiye, Wahab and Price 1987), 26% in Brazil (Santos 1995). In the UK, Skoyles and Skoyles (1987) found waste of materials ranging from 5 to 10% in volume. In Brazil, Soibelman (1993) has monitored the waste of seven materials in five building sites and found values ranging from 5.06% to 11.62% in terms of cost. In Norway costs due to nonconformity, errors, alterations and wastage in the course of the building process are estimate as 10% of the total building cost (Sj∅holt 1998).

Further pressures for reducing waste come from the emergent demands of public opinion and legislation with regard to environmental management. There is an increase demand for development of more environmentally benign products and processes. For instance, in Finland, a graded waste charge based on the harmfulness of the waste had been introduced, making it economically interesting to separate and reduce the amount of waste produced. Additionally, the regulations in that country are now requiring nearly a 10% average improvement in the energy efficiency of buildings (VTT 1997).

COPYING FROM MANUFACTURING OR DEVELOPING CONSTRUCTION OWN THEORY?

Construction has its own particular mix of peculiarities and very often authors use these particularities to defend the distinction of construction from other industries. However, the literature also shows that to place construction peculiarities at a level where they are all determining seems both logically and historically false. Technical change can transform the physical content of production, making previous barriers either non-existent or easier to overcome (Ball 1988). Koskela (1996) argues that most of the peculiarities of construction exist in other domains of engineering and are thus subject to theoretical advancements.

If only certain types of construction can be fully transformed into manufacturing, there will always be certain misfits between the manufacturing literature and the construction practice (Ballard and Howell 1998). In fact, this is one of the main arguments for those that defend the development of a particular theory for construction. Even still, the literature review shows that while construction management has been dedicated to develop its own body of knowledge, it might have done that unaware of the advances in operations management. Thus, the development of construction concepts and techniques carries the risk of alienation and increases the difficulty to exchange ideas with people from other industries.

The strategy adopted in this research widens the scope of core principles of production management at an abstract level. Thus, it avoids the inaccuracies of copying from manufacturing practices and the risk of alienation when searching for special theory for construction.

DEVELOPING CORE OPERATIONS MANAGEMENT PRINCIPLES

The combination of past and new operations management theories has produced a complex portfolio of different strategies to reduce variability. This miscellany generates semantic disputes that lead to confusion and conflict among researchers and practitioners in the field. Indeed, the boundaries of these theories are rarely clear and the overlapping of ideas is not always admitted or pointed out in the literature. Thus, precious resources and brainpower are wasted in trying to get agreement and consensus from the confusing variety of terms and definitions. Truly useful new ideas may be ignored and not seriously considered due to the difficulties in communication caused by the lack of a common theoretical platform.

Propelled by the observations of world-class best-practices, the recent literature brought new prospects to production management when it began to claim that the contemporary theories have a common core (Koskela 1992, Voss 1995). According with Koskela (1992), what varies among modern theories is the way this common core is combined to each different application in practice. Indeed, recent studies have consistently presented evidences that there are some common characteristics among the best production systems world-wide. Such production systems seem to require less human effort, less space, less product development time, less investments in new tools and, at the same time, they exceed the performance of competitors (Womack and Jones 1996).

Construction still lacks investigation into the interpretation and adaptation of this common core to its own reality. In this context, the authors have carried out comprehensive investigation of various core principles and implementation approaches. This paper analysis one of them: the implementation of poka-yoke to reduce variability.

"REDUCTION OF VARIABILITY" PRINCIPLE

DEFINING THE PRINCIPLE

Reduction of variability consists of the identification and elimination of causes for deviations in relation to target values and tolerance limits. This is an important principle because it is interconnected with production management principles. The manifestations of variability in practice range from delays in schedule to dimensional errors in product. Whenever a process is subject to variability, all other performance aspects of that process will vary as well. Even slight variations in quality can influence the customer's perception of the overall quality.

There are two causes of variability in processes. The first type is the **random factors** that are inherent to processes and very difficult or expensive to control or eliminate. They are beyond the operative's control and include factors such as the number of customer's orders per day or slower deliveries caused by heavy rain. The other type of variability is due to causes that can be identified and are easier to control (**assignable causes**). Although both causes may always be present in production systems, it is possible to have procedures in place aimed at reduce or avoid their occurrence (Vonderembse and White 1996).

Taguchi and Clausing (1990) proposed the attack to the **random causes** of variability by designing products in a way that the output would be minimally influenced by those variations. After all, quality losses result mainly from product failure after sale and their reduction is more dependent on product design than stringent control in the production system. This "robust design" would require the identification of the controllable factors that can influence the process output and use this information for developing preventive solutions.

IMPACT OF VARIABILITY IN PRODUCTION SYSTEMS

The cost of variability to society is, in general, far bigger than the cost of the variation itself. It can include, for instance, the guarantee and repair costs and the time clients have lost waiting for those repairs. Taguchi and Clausing (1990) has proposed the use of the idea of 'loss function' in order to measure the loss to society caused by deviations from a 'target value'. According with their definition a distribution of frequency presenting low variability but contained within tolerance limits (process A - Figure 1) is much better than one centred at a target value and presenting high variability (process B - Figure 1). Indeed, when deviations from a target value present low variability (process A), the adjustments are more easy and likely to be successful (Taguchi and Clausing 1990).

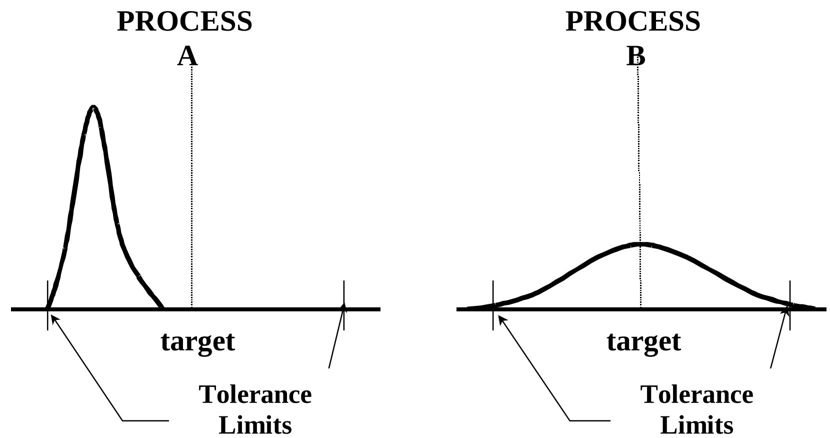

Figure 1: Two Different Types of Process Variability

Variability makes planning and programming a guessing work. Adjustments and corrections caused by variability increase the cycle time, bringing with it costly delays (Shingo 1989). Delays tends to accumulate and usually result in the installation of time buffers between workstations and at the end of the process (Umble 1990).

Variability and uncertainty magnifies the significance of interdependencies within production systems (queuing effect). Thus, it is very important to reduce variability not only in terms of deviations to target values but also in terms of variance in relation to tolerance limits. Variability in the bottlenecks, in special, has a dramatic effect on the capacity of the all production system since the common approach when delays occur is to attempt to match the overall processing capacity with the bottlenecks capacity (Shingo 1988). In production systems that are implanting Just-in-Time, the reduction of variability in products and time is a fundamental requirement. In those systems, everything can come to a halt if one sub-product is not within tolerance limits and delivered at the right time (Vonderembse and White 1996).

APPROACHES TO REDUCE VARIABILITY

"Approaches" for implementing a principle are, essentially, ways of doing things or mechanisms for turning abstract principles and concepts into reality. The literature shows various approaches aimed at reduce variability, but very often these approaches are not strictly focused on variability. In this context, this research adopted the list of heuristic approaches proposed by Koskela (1992), from the VTT Building Technology, Finland, since it presents a more strict relationship with the objective of reduce variability. Koskela's (1992) heuristic implementation approaches include:

- Measuring, Finding and Eliminating the Root Cause of Problems
- Standardisation and
- Installation of Poka-Yoke Devices.

Frank Bunker Gilbreth and Frederick Winslow Taylor are the most important pioneers in the development of the first two approaches. Both researchers were interested in the search for the best way of doing a given task. Gilbreth, in particular, was interested in the study of needless, ill-directed and ineffective motions in construction processes. The motion studies of Gilbreth associated with the time studies of Frederick Taylor gave birth to the "Scientific Management School" (Gilbreth 1911, Taylor 1985). After the 2nd World War, the Japanese companies pushed these approaches towards new limits and used them even more intensively during the re-construction period.

It was during this period that the first systematic developments of poka-yoke devices were registered when cellular manufacturing practices began to emerge. The most prominent pioneer of this approach is Shigeo Shingo, one of the main developers of the **Toyota Production System** (Shingo 1989).

USING POKA-YOKE TO REDUCE VARIABILITY

COMING BACK OF 100% INSPECTION

In the early days of the quality control, there was a strong believes that high quality necessarily implied in 100% inspection. After all, production systems are complex organisations and some errors could go through the production process without notice. Later, people started to realise that this level of inspection is burdensome and time consuming. Then, production systems began to adopt the SPC – "Statistical Process Control" - methods, replacing 100% inspection with sampling inspection (NKS 1987, Monden 1998).

However, the net cost of the errors admitted in the SPC approach may turn to be unacceptable to customers and incompatible with environments of increased high competition (loss function). Thus, nowadays it is observed a coming back of the defenders of zero defects and 100% inspection. A central difference of this movement in relation to the early forms of 100% inspection is that now this activity is designed to be less time consuming by making more intensive use of automatic controls aimed at identify, avoid and reduce problems exactly when they occur.

ENABLING 100% INSPECTION THROUGH POKA-YOKE DEVICES

One of the most common sources of errors in production systems is the human being itself. The list below shows the principal human errors and correspondent actions and some of the alternatives to avoid them, according with NKS (1987):

- **forgetfulness**: alerting operator in advance or checking at regular intervals;
- **errors due to misunderstanding**: training, checking in advance, standardising work procedures;
- **errors in identification**: training, attentiveness, vigilance;
- **error made by amateurs**: skill building work standardisation;
- **wilful errors**: basic education and experience;
- **inadvertent errors**: attentiveness, discipline, work standardisation
- **errors due to slowness**: skill building, work standardisation;
- **errors due to lack of standards**: work standardisation, work instruction;
- **surprise errors**: total productive maintenance, work standardisation;
- **intentional errors**: fundamental education, discipline.

The actions above are important mistake-proofing approaches but still do not guarantee error free production processes. In this way, manufacturing companies started to elaborate electronic and mechanic instruments built into the process in order to guarantee 100% inspection. These instruments are called Poka-Yoke[3] or foolproof, or mistake-proof or fail-safe devices or, **autonomation**. The idea is to *build in* a mechanism to prevent mass-production of defective work in machines or product lines. Some companies even adopt mechanisms that stop the line or machine when abnormalities or defects occur in the workstations (NKS 1987, Monden 1998, Ghinato 1999).

Poka-yoke devices take over repetitive tasks or actions that depend on vigilance or memory and, in this way, they free workers to pursue more creative and value adding activities. NKS (1987) identifies three basic functions of poka-yoke devices: shutdown (stop the process), control (correct) and warning (alert the operator). Micro-switches and limit switches are the most frequently used detection mechanisms used in poka-yoke devices. Limit switches are used to ensure that the process does not begin until the components are in the correct position or to stop the process if a component have the wrong shape. It is also becoming common the use of photoelectric switches to detect the presence of objects, peoples or machines (NKS 1987).

POKA-YOKE IN CONSTRUCTION

RESEARCH METHOD

The researchers carried out six case studies in Brazil and England that focused on the bricklaying process. The researchers developed a protocol to guide the observation systematically. It included a number of tools, such as video recording, photography, work sampling, performance measurements, flow chart and open-ended interviews. This protocol specified the sequence in which these tools should be applied, and guidelines for analysing data and for presenting it. Statistical significance was not considered in the data collection.

The analysis was carried out comparing the practice observed on site with the theoretical propositions (and vice-versa). It employed the process that Yin (1994) calls replication logic, similar to that used in multiple experiments. According with Yin (1989), if both literal and theoretical replication coincide, the results strengthen the validity of the theory. **Literal replication** happens when the abstraction of practice matches with the theoretical proposition. In turn, a **theoretical replication** happens when empirical evidence does not match with the theoretical proposition but shows the outcomes predicted in the theory.

The researcher needed a practical boundary in order to enable comparison across the case studies and establish parameters for judgement. The minimum value established for this indicator was arbitrarily established as equal to the number of stages for the shortest process identified (eight) and the maximum has been established as double that value. The analysis also used relevant information related to the most common production problems identified during the data collection and open-ended interviews in order to infer the type of poka-yoke most demanded by the host companies.

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[3] The Poka-Yoke term comes from the Japanese words yokeru (to avoid) and poka (inadvert) (NKS 1987).

VARIABILITY ACROSS CASE STUDIES

All construction sites presented poor flow performance and the consequences reflected on the indicator of "Process Efficiency" shown on Table 1. The researchers obtained this indicator by dividing the productivity value by the average storage per bricklayer. In this way, this indicator reflected the performance of both value and flow activities as well as their level of synchrony.

Table 1: Quantitative Indicators used to Substantiate the Pattern Matching Findings

ITEM	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6
Country	England	England	England	Brazil	Brazil	Brazil
Number of Photos	160	176	144	96	160	112
Filming (minutes)	58	36	26	22	31	22
Gang Composition	2:1	3:1	2:1	2:1	2:1	1:1
Productivity (m^3/hour) (A)	0,33	0,21	0,18	0,19	0,29	0,23
Average Storage (m^3/hour/bricklayer) (B)	6,12	3,54	5,30	2,62	10,38	6,34
Process Efficiency (B/C)	0,05	0,06	0,03	0,07	0,03	0,04
Waste of bricks/blocks (%)	1	7	14	3	(b)	(c)
% unproductive time	(a)	24	34	26	24	(d)
% auxiliary time	*	28	29	36	24	*
% productive time	*	48	37	38	52	*
Number of Visits to Complete the Operations	3	3	3	3	3	3
Average time between Visits (hours)	120	48	96	72	120	72
Workstation Changeover Time	60	20	60	30	45	45
Number of Process Stages	10	8	8	8	12	12
Total Number of Poka-Yoke devices	1	0	0	2	0	2

Key:
a) In the pilot study (case 01) the work sampling technique was not applied
b) Large number of changes in the design/specifications did not allow the measurement of waste
c) Flow of material simultaneously to different floors offered a logistical constraint to measure waste
d) Use of time-lapse filming instead of work sampling

The gang composition clearly indicated the variations of poor process performance across the case studies. While in Case Study 2 three bricklayers used only one labourer (3:1), Case Study 6 struggle to operate efficiently using one labourer to each bricklayer (1:1). The work sampling technique and time lapse filming results also confirmed the generalised high process inefficiency across the case studies. The numerous photographs taken during the observations helped to substantiate and illustrate these finding.

The high level of variability allied to deficient process design denied the production systems the opportunity of operating in their full potential. There were excessive number of visits to accomplish the main operation (usually 3 visits and 72 ~ 120 hours of buffer time in between) and the speed of these visits was strongly affected by the slow changeover time (max. 60 minutes). Dependencies on upstream and downstream processes amplified the negative effects of variability.

Despite the damaging effects of variability described in the paragraphs above, the process performance the pattern matching approach revealed very few examples of poka-yoke devices. The best case study in this respect used only two devices throughout its eight process stages (see Table 1). All literal replications observed in the case studies did not have support from the necessary complementary practices, as illustrated in Figure 2.

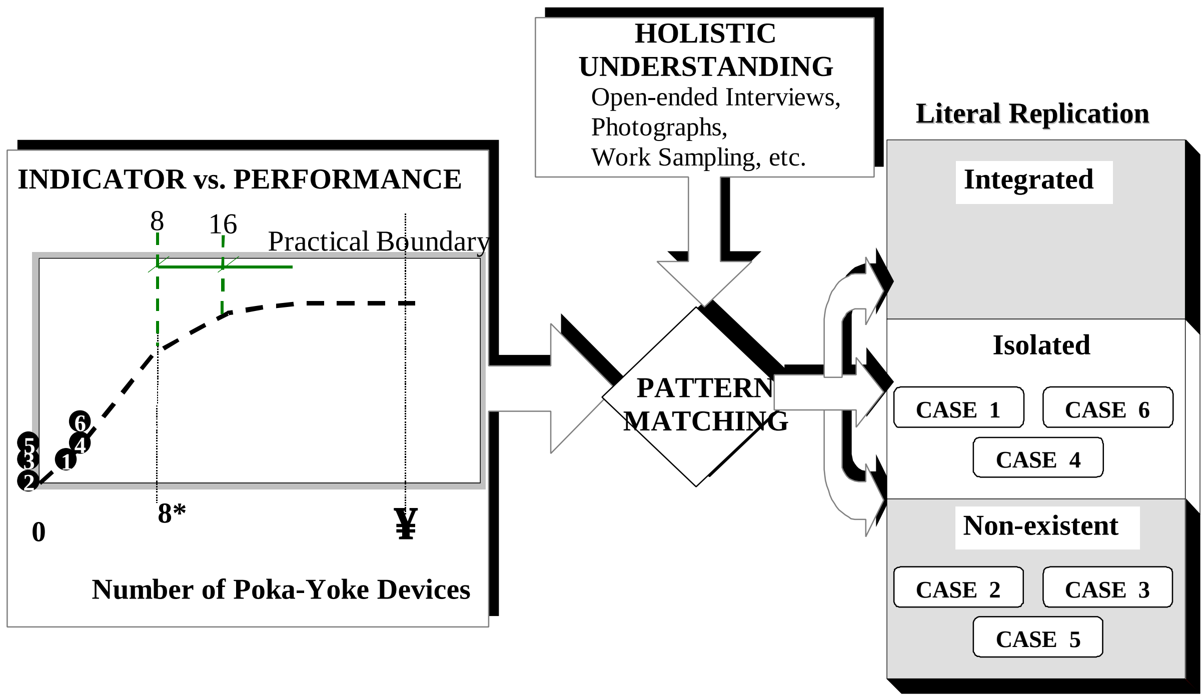

Figure 2: Assessment of Case Studies with respect to Poka-yoke

THEORETICAL AND LITERAL REPLICATIONS IDENTIFIED IN PRACTICE

Figure 3 presents one of the few poka-yoke devices identified in the case studies. This device does not permit the movement of the elevator platform while someone is loading or unloading materials. The elevator can only move when the doors are closed. Additionally, the visual controls attached to this poka-yoke device allow easier identification of the position of the elevator's platform. Yet, this poka-yoke had almost negligible effects on the cycle time or other performance criteria of the construction site analysed since the volume of production was small and the speed of vertical transport was not a process bottleneck.

The case studies presented different levels of machinery on site. The majority of those machines have practically no electronic or mechanical poka-yoke devices. The negative impacts of this situation in the reduction of variability matched with the theoretical predictions. A typical example was the addition of water during the production of mortar, like in the case illustrated in Figure 4. Generally, this activity was carried out manually in this site, without any rigorous control and with direct consequences on the maintenance of a regular quality in the production of mortar. This situation directly affects the productivity of the main value adding activity. Electronic and mechanic devices could be developed to avoid errors of this kind, saving money and time in construction projects.

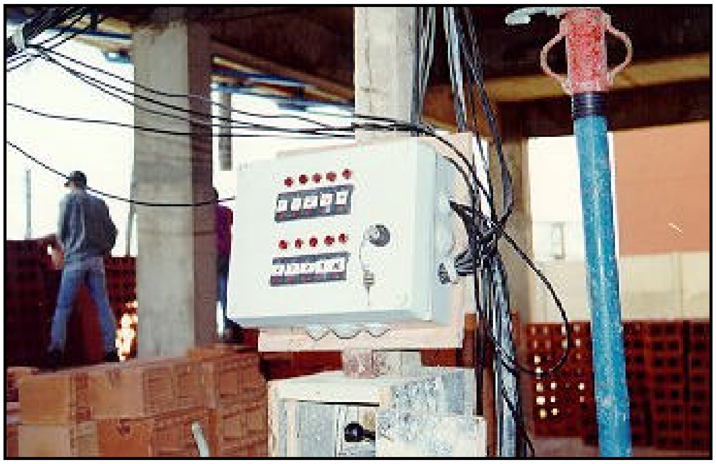

Figure 3: Literal Replication of Poka-Yoke (Case Study 4 - Brazil)

Figure 4: Theoretical Replication of Poka-Yoke (Case Study 3 - England)

The emphasis of poka-yoke devices in manufacturing literature is almost exclusive in machinery. However, the critical observations of construction revealed that the assembling character of construction sites and the reduced number of machines demand a shift of emphasis of this approach. Indeed, there is great scope for building poka-yoke devices on materials and components themselves. For instance, a traditional window factory in the south of Brazil (meta-case) faced growing complaints of problems originated from the lack of face putty[4]. Truly, the subcontractor was often forgetting to put enough putty[5] for glazing glass into the wooden window frames. In order to avoid the occurrence of this mistake again the company developed a new window design where the fixation of the glass necessarily demanded the removal of a component from the window. The removal of this component expose a layer of putty, reducing the risk of mistakes caused by forgetfulness (meta-case).

CONCLUSION

The observations in the case studies suggest that construction makes little use of poka-yoke devices to reduce variability. The few literal replications identified focused almost entirely on the safety aspects of production. In this way, there is great scope for developing mechanic and electronic mistake-proof devices to be applied in the construction. The researchers also concluded that suppliers should reflect on the idea of building poka-yoke devices in their materials and components to guarantee their correct use and application on site.

- **Opportunities for industry -** development of poka-yoke devices to be implemented in existing construction machinery.
- **Opportunities for research -** mapping the sources of variability in the construction processes and define the poka-yoke devices required.

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4 **Face putty, front putty** - The triangular fillet of traditional glazier's putty on the outside of a window pane. (Dictionary of Building 1995)

5 **Putty** - A plastic substance made of whiting (chalk powder) mixed with linseed oil, which hardens on exposure to air, used for glazing glass into wooden window frames. (Dictionary of Building 1995)

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