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Evaluation of Safety, Quality and Productivity in Construction

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Abstract. This paper examines the success indicators of construction projects, safety, quality and productivity, in terms of their implications and impacts during and after construction. First safety is considered during construction with a focus on hazard identification and the prevention of occupational accidents and injuries on worksites. The legislation mandating safety programs, training and compliance with safety standards is presented and discussed. Consideration of safety at the design stage is emphasized. Building safety and the roles of building codes in prevention of structural failures are also covered in the paper together with factors affecting building failures and methods for their prevention. Quality is introduced in the paper from the perspective of modern total quality management. Concepts of quality management, quality control, quality assurance and Six Sigma and how they relate to building quality and structural integrity are discussed with examples. Finally, productivity concepts are presented with emphasis on effective project management to minimize loss of productivity, complimented by lean construction and lean Six Sigma principles. The paper concludes by synthesizing the relationships between safety, quality and productivity.

1. Introduction

Engineers, constructors and facility owners are concerned with the safety of buildings and constructed facilities because of the monetary losses and human tragedies resulting in personal injury, death and suffering. Safety issues may arise during construction due to failure to control the existing site hazards, including collapse of structures during the construction process. In addition, defects in constructed facilities usually lead to serviceability problems, while structural failures can cause catastrophic results. The effectiveness of quality management in all stages of a construction project has a significant impact on safety. It is the goal of the project managers to complete the job by assuring safety and quality, while closely controlling project schedule and cost. This means that

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attention needs to be paid to productivity of the workforce. Unfortunately, knowledge on the relationship between safety, quality and productivity in construction is limited, and because of that there is wide spread assumption that time and expenditures associated with safety and quality in construction compromises productivity; i.e. they delay schedules and increase project costs [7].
This paper aims to provide background information on safety of construction and safety of structures (constructed facilities); describes the principles and tools of quality management and how they are applied to construction projects; covers the associated standards and codes; defines and discusses productivity concepts; and presents a synthesis on the relationship between safety, quality and productivity in construction projects.

2. Safety of construction and structures

Safety is defined as the state of being relatively free from harm, danger, injury or damage. Unsafe conditions in facilities under construction, or in constructed facilities, can be caused by the engineers' failure to develop and implement structurally and environmentally sound designs; performing construction in an unsafe manner on the jobsite; or allowing conditions during service to exceed the structural capacity of the facility. A safety hazard exists when such conditions prevail, and the result is an accident leading to jobsite injuries and fatalities during construction. Similarly, if the safety hazard exists in a structure in the form of an overload, it causes the facility in part or as a whole to become unstable a leading to collapse. Loss of lives and property damage are the common consequences. The role of the design and construction engineers is to anticipate and proactively prevent these happenings.

2.1 Occupational safety

Occupational safety deals with the identification and control of environmental and personal hazards in the work place. According to the US Bureau of Labor Statistics, the recordable injury rate was about 4.0 for every 100 full-time equivalent workers in the US construction industry in 2010, coupled by 774 fatalities in the same year. These numbers have improved significantly over the past few decades due to stricter enforcement of standards, industry training efforts, and advancement of technology. Certain problems have persisted, however; fatalities due to falls are still high (35 percent), followed by struck by and caught in between accidents (13 percent), and electrocution (9 percent) [6], [7].

Efforts to improve site safety are driven by humanitarian, ethical, legal and regulatory, and institutional and image concerns, but the biggest factor is the economic impact. Studies have shown that accidents cost significant sums of money because of increased workers compensation insurance premiums, which are based on the employers' safety records. So, improving the safety of contractors and subcontractors leads to measurable savings in project costs, which are passed on to the project owners (clients). The uninsured (hidden) costs of accidents that have to be borne by the contractors include clean-up, equipment repair, stand-by; work delays and rescheduling; post-accident extra safety supervision; regulatory an d civil fines; legal fees; administrative procedures, investigative reports; transportation to first aid/medical facility; wages paid to injured worker for time not worked; loss of crew efficiency; and training the new/substitute worker. The ratios of the uninsured costs to insured costs have been found to vary between 2 and 20 [7].

Safety hazards arise due to unsafe acts and unsafe conditions, usually in combination. Unsafe acts include unsafe use of tools and equipment; unauthorized operation of equipment; use of defective equipment; failure to use personal protective equipment; unsafe material handling; failure to follow safe procedures; poor housekeeping; and attitude problems (macho, horseplay, inattentive behavior, etc.). A partial list of unsafe conditions encompasses improper guarding (equipment, platform);

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improper illumination, ventilation; hazardous substances (chemicals, explosives, etc.); poor site layout, housekeeping; improper dress; poor maintenance, lockout / tagout practices; and unsafe design and construction [6].

A systematic approach to minimizing and eliminating injuries and fatalities in the worksite is needed, so safety related losses can be controlled. The vehicle to accomplish this goal usually takes the form of a safety program or a safety plan, which can be applicable to project owners, designers (architect/engineer), general contractors and subcontractors. These are policies that can be implemented at the corporate level, or can be project-specific. U.S. federal legislation, through the Occupational safety and Health Administration (OSHA) provides guidelines for safety programs. The main elements emphasized are management commitment and employee involvement, worksite analysis, hazard prevention and control, and safety and health training.

Management commitment starts with the development and communication of a safety/health policy to all employees (signed by CEO) and pervades all operations through instilling accountability for safety, obeying safety rules, reviewing accident reports, conducting regular safety meetings, and involving employees, managers and supervisors in safety activities. Assigning responsibilities to coordinate safety activities, providing resources to accomplish the program goals, integrating safety into business practices (e.g., purchases, contracts, design and development), and recognizing employees for safe work practices are important elements.

Worksite analysis entails evaluating all workplace activities and processes for safety/health hazards, re-evaluating workplace activities when there are changes in processes, worksite conditions, materials and equipment; conducting on-site inspections to identify existing hazards and taking corrective actions; and establishing a hazard reporting system for employees to report unsafe conditions. This task includes investigating all accidents and near misses to determine root causes.

Hazard prevention and control is established by OSHA standards and implemented by training, and site inspections. Well known OSHA standards applicable to the construction industry (29 CFR Part 1926) include General Provisions (Subparts A through D); Personal Protective and Life Saving Equipment (E); Fire Protection and Prevention (F); Signs, Signals and Barricades (G); Materials Handling, Storage, Use and Disposal (H); Hand and Power Tools (I); Welding and Cutting (J); Electrical (K); Scaffolds (L); Fall Protection M); Cranes, Derricks, Hoists (N); Motor Vehicles, Mechanized Equipment (O); Excavations (P); Concrete and Masonry Construction (Q); Steel Erection (Subpart R); Underground Construction, Caissons, Cofferdams (S); Demolition (T); Blasting and the Use of Explosives (U); Power Transmission and Distribution (V); Rollover Protective Structures; Overhead Protection (W); Ladders (X); Commercial Diving Operations (Y); and Toxic and Hazardous Substances (Z). Also, 29 CFR PART 1910, which is applicable to General Industry covers topics applicable to construction, such as lock out/tag out, confined spaces, hazard communication, and so on.

A systematic way to prevent and control hazards is possible through the hierarchy of controls principle, which offers the following approach: 1. Eliminate the hazard (e.g., off site cutting of panel work); 2. Substitute the hazard (replace ladder with scissor lift); 3. Apply engineering controls (sensors and alarms, guardrails); 4. Administrative controls (job rotation, work instructions); and 5. Prescribe personal protective equipment (hard hats, goggles, respirators). Provisions of OSHA standards frequently utilize this principle.

Safety and health training is an integral part of a safety program. An effective training program includes needs assessment (planning); program development including training materials (printed, PowerPoint, video, interactive, demonstrations, etc.); program delivery (classroom lecture, field, online); and training effectiveness evaluation (surveys, pretest / posttest and observations) leading to program improvement. Evaluation can be performed at three levels: Level 1 – Trainee assessment of learning (feedback/perceptions); Level 2 – Measurement of learning (testing, observations); and Level 3 – Reflection in safety performance indicators (leading and lagging) [6].

Structural safety of a constructed facility relates to the understanding and elimination of the causal factors and prevention of failures (partial or total collapse). Some of the catastrophic failures in the US and elsewhere have been quite well documented [16] to [20]. For instance, in 1981, the walkway inside the Hyatt Regency Hotel in Kansas City collapsed during a social function resulting in 114 fatalities and 200 injuries. Inadequate connection detail between steel box beams and hanging rods caused the failure. When the original connection detail was altered by the steel fabricator, load was transferred from roof to the 4th floor creating an overload. The shop drawings had not been properly checked by the engineer of record allowing this to occur. The roof of the Algo Center Mall in Ontario, Canada experienced failure in 2012 due to an overload of a critical connection; this time corrosion due to poor waterproofing of the roof parking surface was the main cause. Two people died and 20 were injured. Forensic investigations revealed that there were construction defects (e.g. missing bolts) and no structural redundancy in design. The collapse occurred as a result of the failure of a simply supported beam. On 21 November, 2013 the roof of the Zolitude shopping centre in Riga, Latvia, collapsed resulting in the deaths of 54 people and injuries to another 41 people. Before the collapse, construction of the green roof of the shopping centre was in progress, as well as construction of underground car parking in the basement, intended for residents of the adjacent apartment building. There were plans for a layer of topsoil 20–30 centimetres thick on the roof; small recreational spots with benches, connected by cobblestone-paved paths, were planned for the resident of an apartment house that was part of the same complex [20]. Although the investigation is not yet complete, three possible causes are being set so far – 1) error in structural design, in particular bolt connection failure of two pieces roof trusses; 2) errors in building procedure and 3) construction of the green roof. On April, 2015 the State Police handed over the results (but not published it) of its massive criminal investigation to the prosecution, asking for charges to be brought against eight persons allegedly involved.

Eldukader and Ayyub [16] conducted a study on structural failures and found that 57% of structural failures resulted in collapse; 44% of failures occurred during construction; 51% of cases involved design errors; and 57% stemmed from construction errors. Structural designers were responsible for 48%; contractor's site staff were involved in 60%. A great majority (86%) of failures were reinforced concrete, while 34% were slabs and plates. Primary causes of failures were listed as inadequate construction methods; poor erection procedures; inadequate connection elements leading to unexpected load behavior; unclear contract information; and violation of contract. Secondary causes were highlighted as natural phenomena (disasters); environmental factors (climate); poor project controls; poor material and equipment usage; and poor workmanship. It was indicated that from a construction management perspective, inadequate planning and supervision, ineffective interpretation/evaluation of safety regulations, poorly defined work responsibilities, poor communications between project participants, insufficient work cooperation, and inadequate training of the workforce contributed to the failures. Engineering factors playing a role were poor site selection and site development, design deficiencies, construction issues, material deficiencies, and operational errors.

Under site selection and development challenges poor land-use planning, insufficient geotechnical surveys, and unnecessary exposure to natural hazards were mentioned. Errors in design concept, lack of structural redundancy, low safety factor, failure to consider a load, calculation errors, misuse of computer software, drafting errors, poor specifications development, and improper connection details were identified as main issues. Material defects covered were material inconsistencies, premature deterioration (including corrosion), poor choice of material, manufacturing or fabrication defects, improper substitutions, and mix-design problems. Finally, alterations to structure, change in use, inadequate maintenance, and negligent overloading were found to be among the critical operational matters contributing to structural failures.

General recommendations presented by Eldukader and Ayyub [16] for the prevention of construction and structural failures included education (including case studies), research, industry association events, failures database and attention to building codes.

2.1. Building codes

Building codes are developed by city, county and state building safety professionals with significant input from the design community and the construction industry. International Building Code (IBC) is currently used in most jurisdictions in the US, and it covers a wide range of topics such as building occupancy classifications, building heights and areas, interior finishes, foundation, wall, and roof construction, fire protection systems (sprinkler system requirements and design), materials used in construction, elevators and escalators, and means of egress. Besides the Building Code (IBC 2009), codes in common use are Mechanical Code (IMC 2009), Plumbing Code (IPC 2009), Fire Code (IBF 2009), Fuel Gas Code (IFGC 2009), Electric Code (NEC2002), Dwelling Code (IRC 2003), and Energy Code (IECC 2003). The primary aim is to establish provisions consistent with the scope of a building code that adequately protects public health, safety and welfare; and subject to the following provisions: (a) do not unnecessarily increase construction cost, (b) do not restrict the use of new materials, products or methods of construction, and (c) do not give preferential treatment to particular types or classes of materials, products or methods of construction.

Local or state government agencies administer and enforce the building code. They appoint building officials to render interpretations of the building code and to adopt policies and procedures in order to clarify the application of its provisions. The building officials perform the following duties: (a) They review applications and issue permits related to building construction work to implement the code; (b) They do all necessary building inspections; (c) They issue notices and orders to ensure compliance with the code; (d) They keep official records related to application, permit, inspections, and so on. Building officials will have the right to enter a building to enforce the code for ensuring building safety. In this process, they are relieved from personal liability for any damage to a person or property as a result of any act or omission in the discharge of official duties.

Construction documents submitted to building officials for obtaining permits include location and layout, site grading, location of utilities, plan and profile, standard construction notes, standard details, and specifications. A permit is not valid until the fees prescribed by law have been paid. A certificate of occupancy is issued after the building official inspects the building or structure and finds no violations of the provisions of the code or other laws that are enforced by the building department.

3. Construction quality management

3.1. Quality management concepts

Quality is associated with meeting project requirements. From a legal perspective, it relates to expertise, liability and standard of care; and from the aesthetics viewpoint, it means the fineness of visible features. When functionality is considered, the designer approaches it by ensuring workable plans and specifications; the owner focuses on project's timely and within budget completion, life cycle costs, and operations and maintenance; the constructors want plans and specifications adequate for estimating and bidding, as well as building the project with fair contract provisions, with timely response to change order requests and inspection reports. Public safety and health, and compliance with laws, regulations, codes and standards are the concern of the regulatory agencies [7].

Quality assurance (QA) and quality control (QC) are processes that are integrated and run together in quality management. QA encompasses all planned and systematic actions to provide adequate confidence that a structure, system or component will perform satisfactorily and conform to project requirements. QC, on the other hand, is a set of specific procedures to assess performance (against requirements) to ensure that the required standards of quality will be met. Generally QA is the responsibility of the owner or his/her designate, aiming to examine the QC methods in place to determine if the contractor is properly controlling work activities, making sure that the QC system and documentation are adequate, and deficiencies are corrected. QC, being a contractor responsibility, requires him/her to develop and maintain an effective QC system, perform all control activities and tests, and prepare acceptable documentation. A competent on-site representative with authority oversees the QC system, evaluating and controlling workmanship and methods to ensure quality is produced as defined in the contract.

Quality management includes processes and activities to establish quality policies, objectives, and responsibilities so that the project will satisfy the needs for which it was undertaken. Although QA/QC systems have existed for a long time, the modern thought of management of quality in a holistic way is relatively new (since 1980's). Total quality management (TQM) is a comprehensive and structured approach to organizational management that seeks to improve the quality of products and services through ongoing refinements in response to continuous feedback framework for implementing effective quality and productivity initiatives that can increase the profitability and competitiveness of organizations. The concept is also applicable to project management [1], [5].

There are many quantitative statistical methods that are employed in the implementation of TQM in quality measurement and improvement. The most commonly used ones are: histogram; Pareto analysis; scatter diagram; affinity diagram; control chart; flow chart; cause-and-effect (fishbone) diagram; and failure mode and effect analysis (FEMA) technique. An important tenet of TQM is doing things right the first time rather than relying on correcting errors. This is associated with the cost of quality, which is the sum of costs related to prevention of errors; appraisals costs for evaluating processes and outputs; failure costs tied with rework and error correction [16].

ISO 9000/9001 and Six Sigma are the two tools that systematically implement the TQM methodology. ISO is the family of standards related to quality management systems (QMS) and designed to help organizations ensure that they meet the needs of customers and other stakeholders. Six Sigma is a highly disciplined process that enables organizations deliver nearly perfect products and services through continued process improvements, where Sigma measures how far a given process deviates from perfection. Higher Sigma capability denotes better performance, the ultimate being 6 standard deviations from the mean which is being error free 99.9996 % of the time in a production situation. The approach to Six Sigma implementation is described by a series of steps involving Design, Measure, Analyze, Improve, and Control (DMIAC), each step involving the mentioned statistical tools [2], [3], [10].

3.2. Quality management challenge in construction

Construction is unique and different from manufacturing, in that structures have longer product life cycle; the owner usually influences production; project participants/stakeholders differ for each project, and each project is first-of-a-kind prototype (no mass production).This requires a unique quality management approach, incorporating relevant codes and permits, owner requirements, design provisions, testing and inspections, and project quality plans. Quality management in construction means making sure things are done according to plans, specifications and permit requirements. No comprehensive quality policy exists that is applicable to the entire industry or large segments thereof, with the exception of nuclear plants and interstate highways [7].

The owner, designer, constructors and regulatory bodies (building authority) must work together to inspect, document and correct deficiencies to manage quality. Contract documents (P&S) communicate design intent and provide technical information on materials, structural elements/assembly and quality requirements for construction and constructed facility construction (building, electrical, plumbing, fire, etc.) Codes present minimum requirements for quality, and construction permits are issued after the P&S review and inspections. Construction and building inspectors ensure that construction meets local and national building codes, zoning regulations, and contract specifications. There may be inspectors on a construction project working for owner, designer, regulatory bodies, or financial institutions.

The quality management plan for the project delineates the roles and responsibilities of project participants, required training and certification, QC/QA processes and systems; shop drawings and other submittals (e.g. samples, temporary structures, traffic plans), testing and inspections, record keeping, verification, correction , reporting and documentation protocols, and quality management audits [9].

4. Construction productivity and lean Six Sigma

Productivity is commonly expressed in terms of quantities produced (output) per employee hour of effort (input). The input can be man-hours, machine time, materials, investment, or capital, while output can be mass, area, volume or length. For construction, productivity can be measured by the number of hours required per item produced (output over input). Construction managers view productivity as the work accomplished per hour for a crew, or at the individual laborer level (e.g., cubic yard of concrete construction completed per crew hours or labour hours worked), which is essential for detailed estimates at the bidding phase. Productivity values can be expressed as an average for the whole project, so comparisons can be drawn within or between projects. A disadvantage is that lots of data may be needed for analysis [14].

Jobsite productivity is influenced by labor characteristics (skill, experience, training, leadership/motivation); project work conditions (job size and complexity, accessibility, equipment availability, breakdown, contractual agreements, culture and local climate); and non-productive activities (indirect labor for supporting construction activity, inclement weather, material shortage, absenteeism, strikes). Productivity is also influenced by design deficiencies, poor coordination, communication, supervision, and scheduling, and stakeholder involvement (e.g., scope changes). Application of lean management principles and tools can prevent productivity losses and improve efficiency. The focus in this approach is on eliminating non-value adding activities and components (waste). Types of wastes identified under the lean Six Sigma approach are: Defects, Overproduction, Waiting, Non-Utilized Talent, Transportation, Inventory, Motion, Extra-Processing (DOWNTIME). The lean tools are comprised of Sort, Straighten, Shine, Standardize, and Sustain (5S) [16].

5. Safety-quality-productivity synthesis

5.1. Lean construction safety

A recent industry survey indicates that there is synergy between lean production and safety management practices in construction [15]. Lean production is based on the Toyota Production System (TPS) to achieve best quality, lowest cost, shortest lead time, best safety and high morale. Lean production tools include Just-In-Time (delivering right items at right time and amount), autonomation ("jidoka" – never letting defective items go to next station; stopping workers and machines when defects are significant), production leveling (reducing variability and inconsistency), and continuous improvement (there is no best, there is always an opportunity to improve processes). These tools can be applied to improving safety management practices such as management commitment, staffing for safety, planning for safety, safety education/training, worker involvement, evaluation and recognition, subcontractor involvement, and accident investigation. Since the lean approach combines quality with productivity, and it can improve safety, one can conclude that safety, quality and productivity can be collectively improved [14], [15].

5.2. Construction safety vs. productivity

The question of how safety is related to productivity often comes up in decisions concerning how much attention and investment must be directed toward safety programs in the construction industry, especially in smaller and mid-sized firms. The following questions relevant to this topic can be considered by the managers.

1. Does safety have a negative or positive effect on construction productivity?
2. What is the significance of the relationship between safety and productivity?
3. Do the expenses associated with a safety program pay off in terms of cost savings for the project?
4. Do safety precautions (compliance) slow down construction work resulting in increased time and costs, and reduced productivity?
5. How can safety and productivity be simultaneously achieved?

Construction projects are expected to simultaneously achieve multiple goals concerning cost, schedule, quality, productivity and safety. These factors are related, while they may be in apparent conflict with each other. Because of pressures on cost, schedule, and productivity, workers may engage in unsafe behavior, believing that this enables them to be more productive. On the other hand, there is strong belief in the industry that no trade off exists between safety and productivity, and in fact they might be synergistic [8], [9], [17], [18], [20].

There is some evidence to support the notion of safety being negatively correlated with productivity. However, there is stronger support for the opposite; that is, safety and productivity are positively correlated, meaning there would be no loss of productivity due to taking safety measures or executing safety programs in a construction project. On the negative correlation side, there are reports in the safety literature that workers may ignore safety due to productivity concerns. In a recent study, safety audits conducted at 200 residential sites showed 59 % non-compliance, meaning widespread disregard for safety. It was found that this came about as a result of concern over taking time off work to learn new safety measures, fear of cost of compliance, and lack of knowledge (inadequate training). In another study, it was observed that managers believed there was not enough time to work safely and safety practices decreased productivity. Research on the impacts of schedule pressures on safety indeed showed increases in injury rate when such pressures are present. Another research study found that workers cut corners on safety to be more productive for fear of losing their jobs. In a study on roofers, it was observed that productivity dramatically decreased when fall arrest systems were used. Workers lost a lot of time adjusting their lanyards on steep roofs resulting in loss of productivity. In a more balanced study, it was concluded that there was a strong negative correlation between safety and productivity when new safety strategies were implemented; however, the correlation turned positive after some time elapsed in the project.

In support of positive correlation between safety and productivity, a U.K. study indicated that productivity losses were higher with safety violations than with preventive safety practices. Similar evidence in a different study suggested that safety management has a positive influence on productivity because of declining task performance by the entire crew in case of injuries. According to this study, damaged equipment and materials, time for additional record keeping, accident investigation and training also slow down production. According to Hinze's [17] distraction theory, workers are more productive when they perceive hazards to be minimal, than working with the perception of being in a high hazard environment. Productivity is compromised when distractions due to hazards turn the workers attention to mitigating safety risks. A recent study on manufacturing productivity vs. safety concluded that management should view safety and operating performance measures as being in concert with each other rather than competing entities. There is more scrap, rework and less employee involvement when safety performance is poor. Based on 18 case analyses, a study by Maudgalya et al. [18] revealed that several organizations realized a payback of their monetary investment in safety initiatives in less than a year. Following the implementation of workplace safety initiatives, organizations observed an average increase of 66% in productivity, 44% in quality, and 71 % in cost benefits. The study concluded that as a business case, safety can assist an organization in achieving the long-term benefit of operational sustainability. Finally, a study by McGraw [14] suggests that contractors are experiencing positive business outcomes from safety programs in terms of shortened schedules, budget/cost savings, increases in project return on investment (ROI), improved reputation, improved market share, and improved project quality.

6. Summary and conclusions

Given that some members and segments of the construction industry emphasize productivity over safety and quality, the main thrust of this study was to review how safety, quality and productivity affect each other, and whether they are in conflict with each other or they are synergistic. Safety was examined in the context of a construction project, as well as during service for constructed facilities. Factors affecting construction and building failures, preventive strategies, and the importance of quality management in securing safe performance for buildings, including the roles of building codes, inspectors and building officials were reviewed. Quality and productivity concepts were evaluated separately and in combination as related to the lean Sigma principles and tools, and this was extended into establishing the relationship between quality, productivity, and safety.

The following conclusions are drawn from this study:

1. Construction safety and productivity are positively correlated in many cases, meaning that investments made into the safety programs do not negatively impact productivity in construction, although some situations exist where safety precautions might slow down productivity.
2. Safety management and quality management are integrated, and they work together. Safe projects will support quality efforts.

3. Since the lean principles apply both to safety and quality in construction, and they play a significant role in increasing the productivity, there is synergy between these three facets of construction projects.

The information on the relationships between safety, quality and productivity in construction is quite dispersed and fragmented. Further research into safety, quality and productivity relationships is warranted, and is hereby recommended.

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