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Constructional Designs of Architecture Students – Were Building Subsystems Successfully Integrated During the Project Process?

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Abstract: Integration problems between building subsystems designed by different specialists may arise when not properly coordinated. Alongside their design duties, architects often have control/coordination responsibility to avoid these. Gaining experience in integrating building subsystems is an objective of the Construction Project course in the Istanbul Technical University Bachelor of Architecture Program. Final submissions of the author-led groups were evaluated to determine design deficiencies and integration problems observed and to discuss students' performance in subsystem integration. Using a classification framework generated for determining the types of subsystem integration, design deficiencies and integration problems based on literature, 20 student projects were reviewed in this respect. Drawings of each project for the architectural, structural, heating and plumbing systems were assessed within themselves and in pairs to find inconsistencies. Regarding the integration problems identified, opinions of a few professionals on their significance in causing rework were taken via a questionnaire to assist the discussions. Students' performance was assessed using both quantitative findings regarding the number and type of design deficiencies and integration problems identified and professionals' opinions. In total, 12 design deficiencies and 20 integration problems were identified. Among the deficiencies, the occurrence rate of errors was higher than that of the omissions (i.e. 61% and 39.2% respectively). Among the integration problems, the structural system was always a component of the subsystem pairs with a high occurrence rate of problems (i.e. >50%). Regarding different types of integration problems, omission was the least commonly observed problem followed by error, and soft and hard clashes respectively.

Keywords: Building fabric, Technical design, Systems integration, Architecture education, Design deficiency, Clash detection

1.Introduction

In building design, various actors take design responsibility for different subsystems of the building. Their design processes often continue separately and concurrently. This separation can lead to unintended interferences occurring between these subsystems that need to be solved at the construction site unless detected during design (Gross, 1994). These interferences, i.e. poor physical coordination and integration between different subsystems, are still an ongoing problem and may cause construction rework which in turn can cause cost increase and rescheduling.

Assaf et al. (2018), for instance, based on interviews with consultants, ranked the lack of cross-disciplinary coordination 3rd in significance in causing rework. Ye et al. (2015), based on semi-structured interviews with experts, in addition to 'poor coordination of design team members' that was 6th in rank in causing rework, identified 'design error/omission' as another cause, which was 5th in rank. Asadi et al. (2023), based on surveys, similarly listed 'incomplete design, any omission in the design or construction process' and 'error in design, drawings, and specifications/error in construction' among factors with an effect on rework.

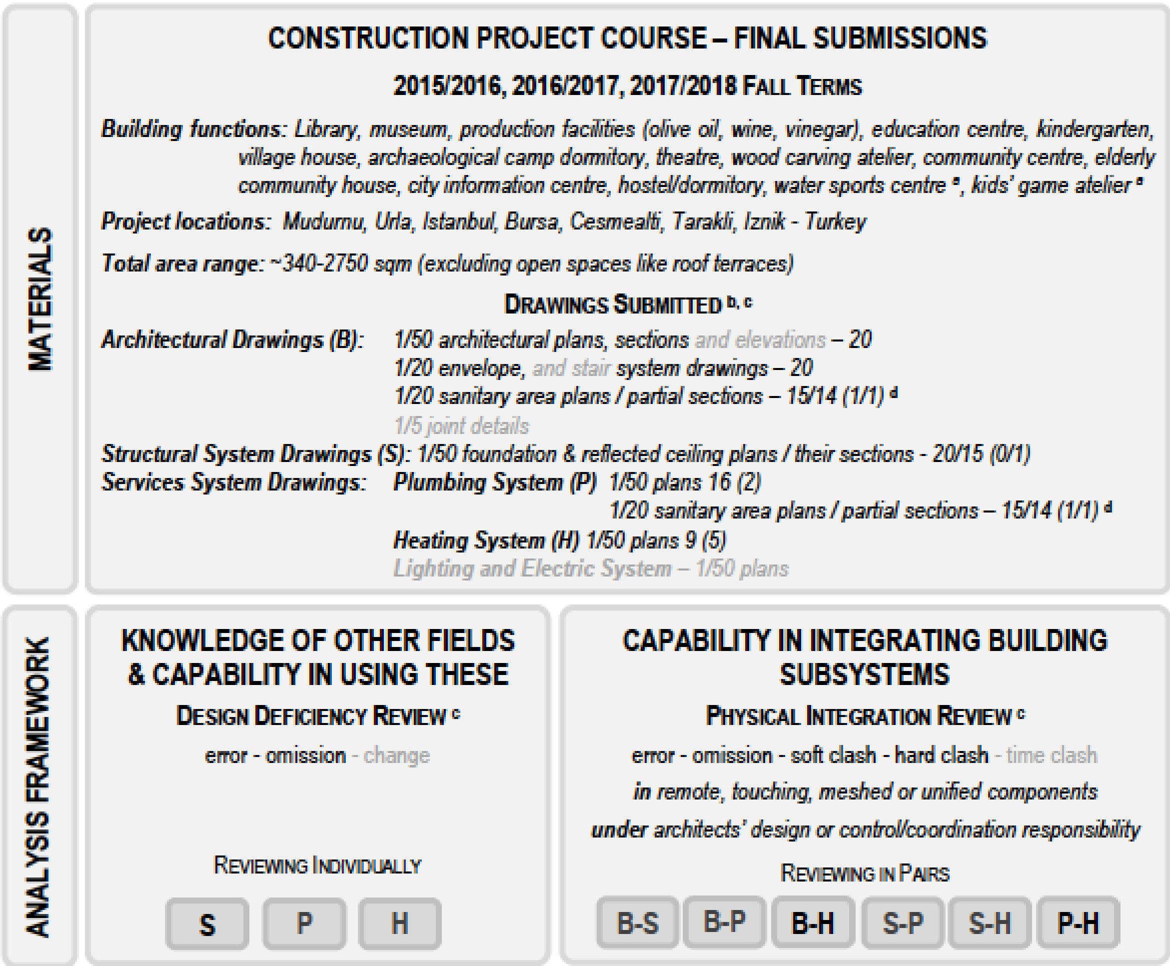
Research studies are being made to overcome these problems, especially in the information technology field concerning the physical coordination problem. Clash detection tools available for Building Information Modelling (BIM) applications provide opportunities to resolve that (e.g. (Merschbrock & Munkvold, 2015; Jafari, Sharyatpanahi, & Noorzai, 2021)). Yet, studies also show that even when BIM is adopted, there are still some barriers. Akponeware & Adamu (2017) stated based on a survey that working in isolation from each other was the most important cause of clashes. Clash detection tools are also not precise enough yet, and may report irrelevant clashes. Therefore, studies to improve their precision are being done, e.g. (Hu, Castro-Lacouturea, & Eastman, 2019).

The curriculum of architecture education contains technical courses to equip the students with the necessary knowledge of the interacting fields, in varying proportions according to the different architecture schools. These courses and other courses in the curriculum also aim to provide an insight into an integrated project, where different subsystems are properly integrated both functionally and physically. There are also active efforts for a better integration of the knowledge of the interacting fields. Design/project-based learning is one of the strategies used for this purpose. Ünay and Özmen (2006), for instance, discussed their strategy of taking the architectural design studio into the centre to teach structural systems to the architecture students where structure instructors have participated in the design studios. Similarly, Uihlein (2013) explained the design-based methodology employed in the advanced structural planning course in architecture education to create a link with structural engineering. Integration of the architectural design course and the structural and technology courses through the assignments is another approach to this end. Bakar et al. (2023) assess the use of this approach during the term for integrating architectural design studios and various technology-related courses. Their findings indicate that the students found this approach effective for gaining an understanding of technical subjects, yet expressed a sense of lack of proper integration of those subjects into the design. Likewise, Metin (2023) presented the use of assignments and studio work for the integration of the building technology knowledge, but with an integration across terms by using the previous architectural design studio courses outputs and their step-by-step development through various technology courses. In these studies and others, some illustrative examples of student work or the students' views on achieving these objectives are usually presented. Nevertheless, given the ongoing problem of unintended interferences faced in the professional field, there is a need for a systematic review and analysis of student works to determine the students' performance in integrating different subsystems at least physically.

At Istanbul Technical University, in the Bachelor of Architecture Program (ITU-BArch), a fourth-year course named Construction Project, besides other objectives, aims to teach integrating architectural systems with remaining building subsystems designed by other specialists. This is carried out in a design-based learning environment, and students usually experience the full design process at a small-sized building. In view of the fact that eliminating the problems of unintended interference and design error is found important in the construction industry, especially in minimising construction rework, the outputs of this course given by the author were systematically evaluated in these respects, and the findings are presented here. Additionally, as a NAAB (National Architectural Accrediting Board – US) Internationally Certified program, graduates have to gain a certain understanding and/or ability regarding these systems (NAAB, 2019). Therefore, their ability to use the knowledge about these systems in their designs was also investigated.

2. Materials and method of the assessment

The objectives of the Construction Project course given each term by various academics are; (i) developing skills to create architectural solutions considering technical, legislative and aesthetic issues, and the skills to develop and integrate subsystems, (ii) learning building material selection, and (iii) gaining experience in technical design and preparation of design documents. Each term, each group's (ca. 6-12 students) study subject and work scope are determined individually by the leading academic. Here, all final submissions of the groups led by the author in three years are considered. The analysis was limited to three years as its findings may affect the author's way of tutoring in the proceeding terms. 20 projects were evaluated in total, and information about those is given in Figure 1.



a: Projects designed by student pairs. **b:** The numbers following the drawing explanations indicate the number of projects containing those drawings, and if given, the numbers in parentheses indicate the number of projects, where only some of the associated drawings were present. **c:** The items given grey in colour were not assessed here. **d:** These drawings were considered under the plumbing system in the design deficiency review, and under the architectural system in the physical integration review.

Figure 1: *General information on the projects and the analysis framework.*

In these groups, students individually designed and detailed a small/medium-scale building, except for the two projects worked on in pairs. Building functions were decided by the students considering the necessities of project locations. During the term, following building programme preparation, they conceptually designed the building and its structural system accordingly. The building element assemblies were then decided, and followed by the conceptual design of services systems. Finally, they worked on the joint details of building elements. The final project items submitted are listed in Figure 1. All structural and services systems drawings could not be submitted sometimes due to time shortages. Thus, project counts with relevant drawings are also given in the figure.

The assessment of these 20 projects was carried out in four main stages, which are; (i) determining the analysis and classification framework based on literature, (ii) reviewing the projects considering the framework, (iii) getting professionals' _opinions on the integration problems identified via a questionnaire, and (iv) discussing the findings quantitatively and qualitatively. The structuring of the framework and the steps followed in the succeeding stages are detailed in the following subsections.

2.1. Determination of the analysis and classification framework

The objective of the project review was twofold; to understand (i) the knowledge of students in other fields and their capability in using these in their designs, and (i) their capability to integrate building subsystems (Figure 1). For both purposes, a building subsystem classification was needed, and benefiting from the building fabric and building element classifications given in (ISO, 2016; Rich & Dean, 2015), building subsystems were accepted to be (i) structural system, (ii) services systems, and (iii) building elements system covering walls, roof, floors, windows/doors, and stairways/ramps. The latter system is mainly under the architect's design responsibility and is therefore called 'architectural system' in the text sometimes. The former systems are designed by engineers with the direction, control and/or coordination of architects.

Concerning the first objective, the course prerequisites are the individual courses on structural and service systems, in addition to those on building elements. They practice using previously gained knowledge by conceptual design and drawing of structural and services systems for their projects. Therefore, their success in these drawings can be taken into account for assessing their knowledge and capabilities on these subjects, and the number of design deficiencies can be used as an indicator.

Design deficiencies, as defined by Lutz et al. (1990) are "the conflicts, omissions, or errors in the design documents". These are stated to have potential impacts on the building's quality and the construction phase such as the rework necessity. They additionally referred to 'disagreements between drawings, specifications' and 'interdisciplinary coordination errors' as two of the commonly seen deficiency types, where the latter is directly related to the second objective of this study; subsystem integration. Burati Jr. et al. (1992), in their study on quality deviations, stated 'error', 'omission' and 'change' as the types of rework causes, and benefiting from their classification and explanations, the design deficiency types to be searched in the projects were decided to be as follows as also given in Figure 1:

- error - an incorrect item, i.e. a mistake;
- omission - any part of a system that has been left out.

Concerning the second objective, different integration types are present, even at the 'hardware-level' as used by Bachman (2003). Examples of these are; performance integration concerning the delivery of shared function(s) (Bachman, 2003; Hartkopf, Loftness, & Mill, 1986), visual integration dealing with the aesthetical arrangement of exposed components mostly (Bachman, 2003; Rush & Stubbs, 1986), physical/geometrical integration considering the spatial relations and connections of components (Bachman, 2003; Rush & Stubbs, 1986). Here, the physical/geometrical integration considering spatial relations and connections of these subsystems and their components was investigated. To analyse in what type of system interactions the problems were mostly observed, Rush and Stubbs' (1986) subtypes were adapted to define the systems' ordinary relation as follows by combining two of their subtypes:

- remote - systems are physically separate but still coordinated functionally;
- touching - one system rests on another, and/or attached by adhering or mechanical means;
- meshed - systems occupy the same space;
- unified - systems share one physical form.

Regarding physical/geometrical integration, 'clash detection' is the process of checking spatial relations of building subsystems and components i.e. physical interaction between them. It also covers control of time-related issues. In general, three different types of clashes are mentioned in the related literature as follows (Allen, Becerik, Pollalis, & Schwegler, 2005; Staub-French & Khanzode, 2007; Tommelein & Gholami, 2012; Wang, Wang, Shou, Chong, & Guo, 2016):

- soft/clearance clash - components are close to each other beyond the allowable limits or spatial conflict of components will be solved during construction as a common practice;
- hard clash - components that need to be remote or touching are unintentionally sharing the same space, fully or partially;
- time/schedule-clash - spatial problems related to constructability and operability of the facility or scheduling clashes of the workforce, tools, etc.

Here, to understand the students' success in integrating building subsystems, the soft and hard clash counts were used as indicators. As interdisciplinary coordination problems are also mentioned under design deficiencies, and since some problems may not lead to a clash depending on the design conditions, error and omission were also included in the integration problem types (Figure 1). Additionally, to investigate in which responsibility of the architect the integration problems are mostly observed (i.e. design versus coordination/control), this kind of grouping was also included in the analysis.

2.2. Review of the projects

In the analysis, initially, the structural, plumbing and heating systems drawings of each project were reviewed individually to determine, list, and group the design deficiencies (Figure 1). Regarding these;

- In structural system (S) drawings, the discrepancies between reflected ceiling/foundation plans and their partial sections (i.e. errors), and fully missing components for an appropriate load-bearing performance (i.e. omissions) were searched for. Components present on plans but missing in sections, or vice versa were considered drawing mistakes and called errors.
- Regarding plumbing system (P) drawings, only the omissions were searched for in 1/50 layout designs, as sections were not requested. In 1/20 drawings both design deficiencies were searched for when partial sections were available. While listing the problems, each different type of missing plumbing component was considered a separate problem to be more definite.
- In heating system (H) drawings, 1/50 general layout plans were checked, again only for the missing main system components (i.e. omissions) since schematic sections were not requested, and each missing component was defined as a separate problem, similarly.

In the second phase of the project review, architectural drawings (B), structural system drawings, and services systems drawings were comparatively reviewed in pairs to determine and list integration problems (Figure 1). In these reviews, the list of commonly observed problems prepared regarding the projects of the 2015/2016 fall term was used as a base (Edis, 2016). While listing an integration problem, the ordinary relation between the associated components, its type in terms of being an error, omission or clash, and the architects' duty in this problem were also determined.

In both reviews, the existence of a problem in a project was counted, independent of how many times or at how many places it was observed at that project. The occurrence rate of each problem was then calculated considering the total number of projects with relevant drawings.

2.3. Getting the opinions of professionals

To get some insight into the perspective of the associated community in Turkey and provide a basis for discussing the importance of the observed integration problems, the opinions of a few practising architects, civil engineers, and architect academics were taken through a survey of voluntary participation, using the integration problems list prepared in the previous stage. In the questionnaire prepared for this purpose, the significance of these integration problems in causing construction rework was asked without giving any drawing examples from the final submissions of the students. A five-point Likert scale was used to define the significance of 20 problems listed, where one (1) indicated 'totally insignificant', three (3) indicated 'neither insignificant, nor significant', and five (5) indicated 'very significant'. The averages of the answers of seven respondents with different professional backgrounds (i.e. two academic and three practising architects, two practising civil engineers) were then used briefly in the discussions concerning the outputs of the integration problem review, i.e. the findings of the second phase of project review. The responding architects, all of whom graduated from ITU-BArch, had 21-23 years of experience, and the civil engineers' experiences were between 9 and 13 years.

2.4. Discussion of the findings

The findings of the design deficiency review were discussed briefly considering the associated NAAB student performance criteria (NAAB-SPC) and the number of deficiencies together. An overall assessment was also made to determine in which system's application the students were more successful, and whether the findings were similar to the cases regarding professional practice.

Regarding the findings of the integration problem review, initially, the type of integration problem, e.g. soft or hard clash, was discussed considering the interaction type between the components, construction phases and/or the availability of proposing a solution. The professionals' opinions were also considered to investigate and discuss whether there was a mismatch between the classification and the significance rate. Additionally, the relation between the component interaction type and integration problem type was examined to determine whether there were any definite patterns. An overall assessment was made finally to determine system pairs with most problems.

3. Findings of reviews and discussions

The review findings regarding two objectives are given and discussed below in two main subsections.

3.1. Design deficiency review

Errors and omissions were searched in the individual review of structural, heating and plumbing systems drawings as design deficiencies. Deficiencies found in this respect and their occurrence rates are given in Table 1, and explained and discussed in the following subsections together with some examples from the projects. In these examples, issues related to integration problems were noted too when relevant. In all drawings given, some items such as construction lines, codes, etc. were removed from the originals, when necessary to improve the problem visibility, and author-made cuts were shown with dotted lines.

3.1.1. Structural system drawings

Among the deficiencies, errors were remarkably more common than omissions, and among the errors, S_1 size/shape/position discrepancies had the highest occurrence rate, some of which were caused by considering a different component while aligning or drawing (Figure 2-A). Regarding missing components in partial sections, S_2 concerning those in elevation view (Figure 2-A) was considerably more common than S_3 concerning those in section view (Figure 2-B), which might show that students focused more on items in section view, rather than the ones in elevation view. Regarding the omission of components necessary for proper loadbearing performance (S_4), the problem was identified to occur in four projects. In two of these projects, considering that a major change was made in the architectural design after the initial conceptual design of the structural system, the omission of necessary structural members was most likely because of not rechecking the structural design after that major change, rather than a lack of knowledge on the subject (Figure 2-C). NAAB-SPC expects the ability to apply the appropriate structural system (NAAB, 2019), and among these design deficiencies, S_4 is an important indicator of students' knowledge and capabilities. It had the lowest occurrence rate together with S_3, and when thought together with the fact that half of these cases were presumably the result of forgotten rechecks after a major revision, it can be said that almost all students had the necessary understanding of structural behaviour and the ability to apply structural systems.

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Table 1: *Design deficiencies in drawings*

Code	Design deficiency observed (scale of drawing when necessary)	DT	CP_D	CP_T	OR (%)
S_1	Components having different sizes/shapes/positions in plans and partial sections, or in different structural plans	E	11	16	69
S_2	Components present on plans but missing in elevation view in partial sections (i.e. column, beam)	E	10	15	67
S_3	Missing structural planes partially/fully in the partial sections	E	3	15	20
S_4	Missing columns or beams necessary for proper load-bearing performance	O	4	20	20
P_1	Missing supply pipes and/or drains for some locations (excluding rainwater capture and use) (1/50)	O	4	18	22
P_2	Missing pipes to and/or from rainwater storage tank (1/50)	O	7	15	47
P_3	Missing some/all cleanout manholes and/or their connection to city sewage system (1/50)	O	9	17	53
P_4	Missing water/rainwater storage tank (1/50)	O	2	17	12
P_5	Missing horizontal supply pipes and/or drains (1/20 plans and/or sections)	E O	13 3	16	100
H_1	Missing chimney	O	6	10	60
H_2	Missing fuel supply/storage	O	10	10	100
H_3	Missing horizontal distribution pipes to radiators/vertical heating system pipes	O	2	10	20
DT: Deficiency type, **CP_D:** the number of projects with deficiency, **CP_T:** The total number of projects with relevant information, **OR** (Occurrence Rate): CP_D/CP_T in percent, **E:** Error, **O:** Omission					

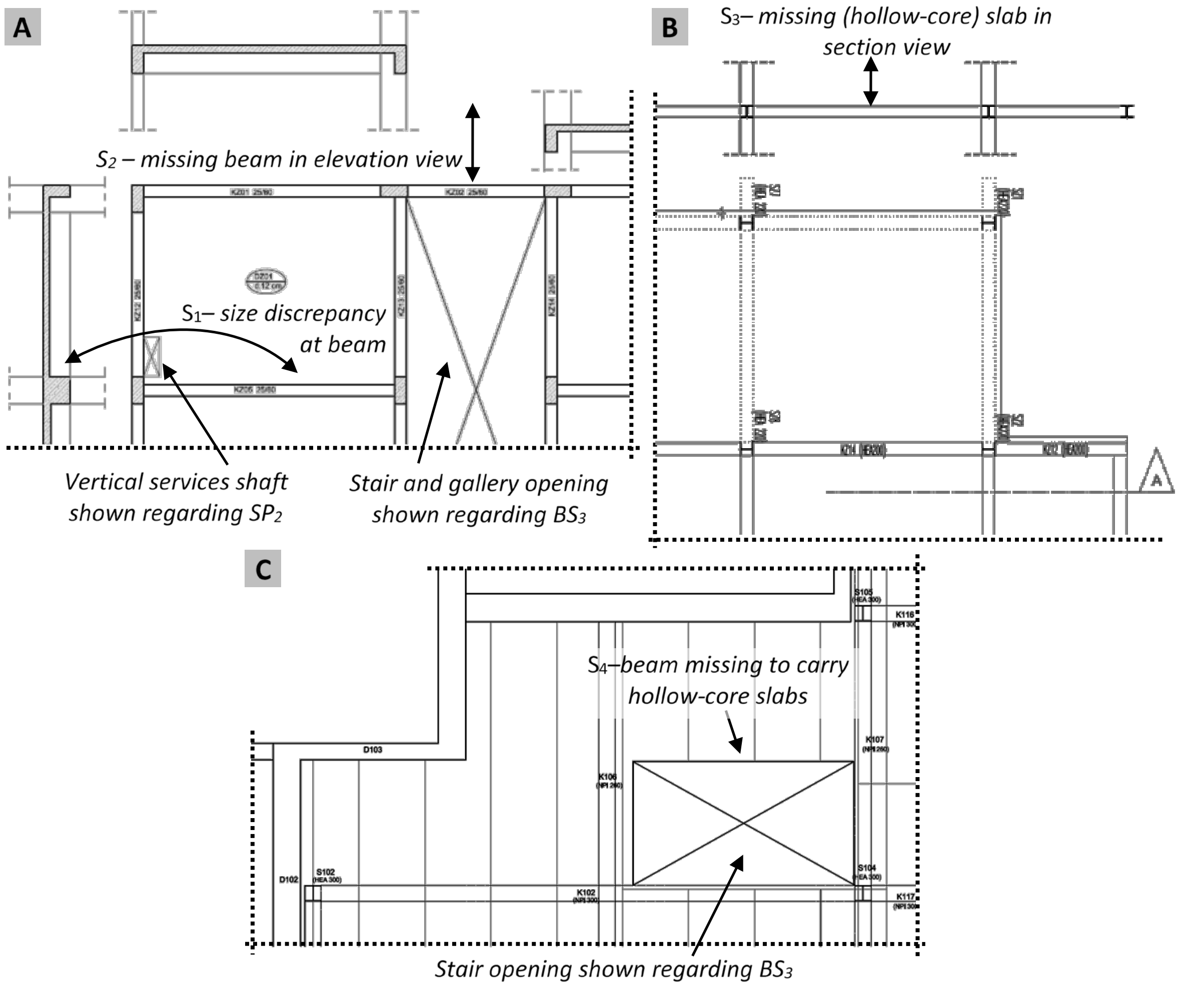

Figure 2: *Examples of structural system design deficiencies.*

3.1.2. Plumbing system drawings

Within the problems regarding 1/50 plans, omissions of manholes (P_3) and connections to/from rainwater tank (P_2) had the greatest occurrence rate respectively, with a considerable difference from others. About P_3 (Figure 3-A), in five projects, at least one manhole was drawn which shows that students knew its necessity, but were not precise about where to put or how many to use. About P_2, the rainwater tank-roof connection was omitted mostly (5/7) without any apparent reason. As a whole, missing supply pipes and drains in 1/20 sanitary area drawings (P_5) had the highest occurrence rate with 100%. However, in most of the projects with the P_5 problem, pipes and drains were properly shown in their 1/50 plans (Figures 3-B and C). Therefore, regarding deficiency type classification, P_5 observed in projects with proper 1/50 plans were called errors, while the ones without relevant 1/50 plans were called omissions.

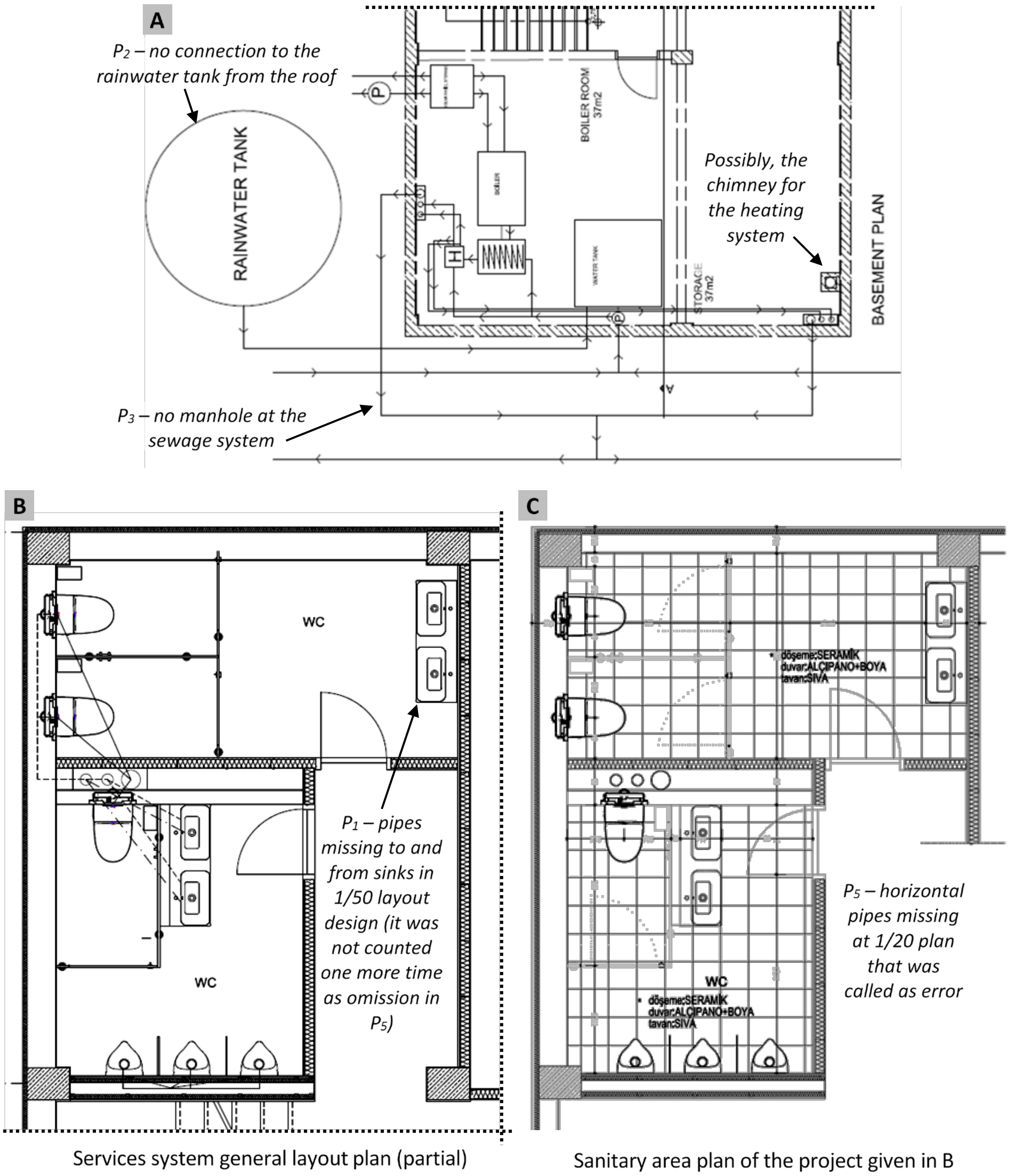

***Figure 3:** Examples of some plumbing system design deficiencies*

NAAB-SPC expects an understanding of the basic principles and appropriate application of building services systems (NAAB, 2019). When errors regarding P_5 are excluded, most students can generally be said to have the necessary understanding of the fundamental application principles of the plumbing system and can associate them with their designs, as the entirely missing component counts were too small.

3.1.3. Heating system drawings

As the most common design deficiency, in none of the projects with relevant plans, the fuel supply connection to the heating unit from the city supply system or fuel storage area necessary in one project was provided (H_2).

Similarly, in most projects with relevant plans, there was no chimney for the heating unit (H_1). These might show that students usually focused on the internal connections of the system, rather than their external connections when considered together with the small occurrence rate of missing pipes reaching inhabited floors.

In summary, considering that inhabited floor plans did not contain deficiencies, it can be said that the necessary understanding had been gained about most principles and components of the heating system. However, in the future, students' attention needs to be directed more to external connections.

3.1.4. Comparative discussion of design deficiency review

For each deficiency type in each system, cumulative sums of the project counts with deficiency and the total number of projects with relevant information (i.e. ΣCP_D and ΣCP_T respectively) were examined for a comparative analysis (Table 2). When all systems were considered together, the occurrence rate of error was considerably higher than that of omission. Love and Li (2000), in their project analyses, found similarly that the number of design errors was considerably more, which resulted in higher rework costs. Likewise, in the study of Burati Jr. et al. (1992), the design error rates were considerably higher than design omission rates. Considering all, it can be said that a pattern similar to that of real-life projects was present in the students' projects, where errors were more common than omissions. From the educational perspective, the smaller rate of omissions can be considered a good sign of gaining the necessary knowledge on the principles and applications of these systems.

When the total occurrence rate of both deficiencies was analysed for each system, the students were observed to be more successful in structural system design with the lowest occurrence rate of 40.9%. However, when P_5 and H_2 present in all relevant projects were excluded from the analysis, the deficiency-free project count was higher for plumbing and heating systems (i.e. five and four projects respectively), while there was only one deficiency-free project for the structural system. This also shows that the number of design deficiencies can be reduced in the future by stressing more on issues regarding P_5 and H_2.

3.2. Integration problem review

Error, omission, and soft and hard clashes were searched in the drawings as integration problems. Problems observed in this respect while reviewing the building subsystem drawings in pairs are given in Table 3. Their occurrence rate and professionals' opinions (PV) on their significance in causing rework are also given in the same table. The simple averages of the responses are presented for this purpose where 3 was used in the questionnaire to indicate 'neither insignificant, nor significant', and 5 to indicate 'very significant'.

Table 2: *Total numbers of design deficiencies.*

	Structural System			Plumbing System			Heating System			All Systems		
	ΣCP_D	ΣCP_T	OR (%)	ΣCP_D	ΣCP_T	OR (%)	ΣCP_D	ΣCP_T	OR (%)	ΣCP_D	ΣCP_T	OR(%)
Errors	23	46	50.0	13	13	100	0	0	0	36	59	61.0
Omissions	4	20	20.0	25	70	35.7	18	30	60.0	47	120	39.2
Errors + Omissions	27	66	40.9	38	83	45.7	18	30	60.0	83	179	46.4

ΣCP_D: Cumulative sum of CP_D ΣCP_T: Cumulative sum of CP_T OR (Occurrence Rate): $\Sigma CP_D/\Sigma CP_T$ in per cent

Table 3: *Integration problems in drawings.*

Code	Integration problem observed*	AR	IT*	IPT*	PV	CP_I	CP_T	OR (%)
BS_1	Structural components with different sizes/positions in structural and architectural drawings	DR	R (6) T (7)	E (6) E (4) C_H (3)	4.71	13	19	68
BS_2	Missing (10) or additional (3) beams in architectural sections	DR	R (12) T (4)	E (12) C_S (4)	4.29	12	20	65
BS_3	Missing stair/gallery opening at structural slab	CR	M	C_H	4.83	9	20	45
BP_1	Missing some/all vertical services shafts at some/all architectural plans [a] (7) or vertical services shafts at different places in architectural and plumbing plans [b] (1)	DR	M	C_s (8)	4.71[a] 4.57[b]	8	20	40
BP_2	Insufficient wall thickness for embedding pipes/drains/reservoir	DR	M	E	4.71	5	17	29
BP_3	Insufficient suspended ceiling depth for drains	DR	R	C_s (1) C_H (1)	4.71	2	11	18
BP_4	Window/door partly blocked by vertical services shaft	DR/ CR	R	C_s (1) C_H (1)	4.43	2	19	11
BH_1	Underfloor heating tubes beneath e.g. stair-floor connection, masonry wall	CR	R	C_S	4.17	2	7	29
BH_2	Underfloor heating tubes beneath stud walls	CR	R	C_H	3.29	1	5	20
BH_3	Missing/insufficient underfloor heating system layers in architectural sections	DR	T	C_S	4.14	1	12	8
BH_4	Missing chimney in some architectural plans	DR	M	C_S	4.71	1	7	14
SP_1	Missing some/all services shaft openings at structural plans	CR	M	C_H	4.71	13	20	65
SP_2	Unsolved integration of columns/ loadbearing walls and horizontal supply pipes/drains	DR	R	O (6) C_H (2)	4.00	8	17	47
SP_3	Vertical (4) or horizontal (1) supply pipe/drain or services shaft (3) passing through the beam	CR	R	C_H	4.86	8	19	42
SP_4	Missing (5), additional (1) and/or wrongly located (3) structural components at sanitary area drawings	DR	R	E (4) O (5)	4.71	8	16	50
SH_1	Missing opening at floor slabs for the heating system vertical pipes	CR	M	C_S	4.00	11	14	79
SH_2	Missing chimney opening at structural plans	CR	M	C_H	4.57	4	7	57
SH_3	Chimney (1)/vertical heating pipe (3) passing through beam	CR	R	C_S (2) C_H (2)	4.86	4	15	27
PH_1	Underfloor heating tubes under toilet basin with 'S' trap	CR	R	C_S	4.29	2	7	29
PH_2	Overlapping / too close main distribution pipes		R	C_S	4.43	4	9	44

AR: Architects' responsibility **IT:** Interaction type **IPT:** Integration problem type
PV: Professionals' view **CP_I:** Projects with integration problem **CP_T:** Projects with relevant information
OR: CP_D/CP_T in per cent **DR:** Design/drawing responsibility **CR:** Control/Coordination responsibility
R: Remote **T:** Touching /connected **M:** Meshed **U:** Unified
E: Error **O:** Omission **C_S:** Soft clash **C_H:** Hard clash
**: The number of projects with that specific situation is given in parenthesis when necessary to distinguish*

3.2.1. Architectural and structural systems' integration

The most common problem in the architectural drawings was the position, size or shape difference of structural members (BS_1). Among these, the remote and touching relation counts were close to each other. In all remote relations, the problem was called error, but in touching relations, the construction stages were considered to decide between error and hard clash. The steel sheet's directional problem given in Figure 4-A was called an error for instance, while the upright beam and dropped slab use in Figure 4-B was called a hard clash since the green roof construction would be impossible or difficult if this variation was not noticed before structural member construction. The missing and/or additional beams in architectural sections (BS_2) were the second in line. The missing beams were usually remote from other architectural components, without any clash problem risk (Figure 4-A & B). Thus they were called errors. In touching relations, either there was a wall underneath the beam, or the suspended ceiling was attached to the beam's vertical sides. Considering the construction stages, they were decided to cause a soft clash. Extra beam(s) in some projects

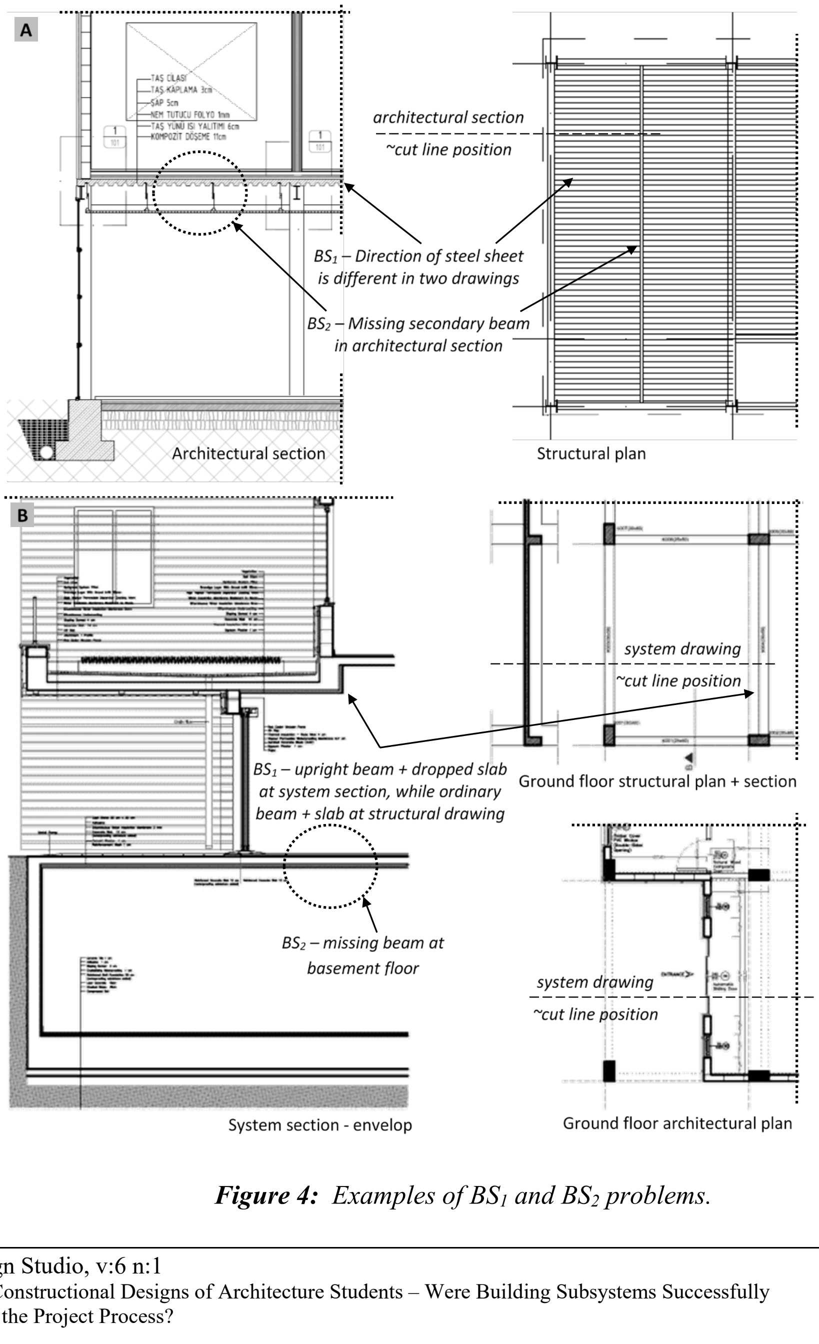

***Figure 4:** Examples of BS_1 and BS_2 problems.*

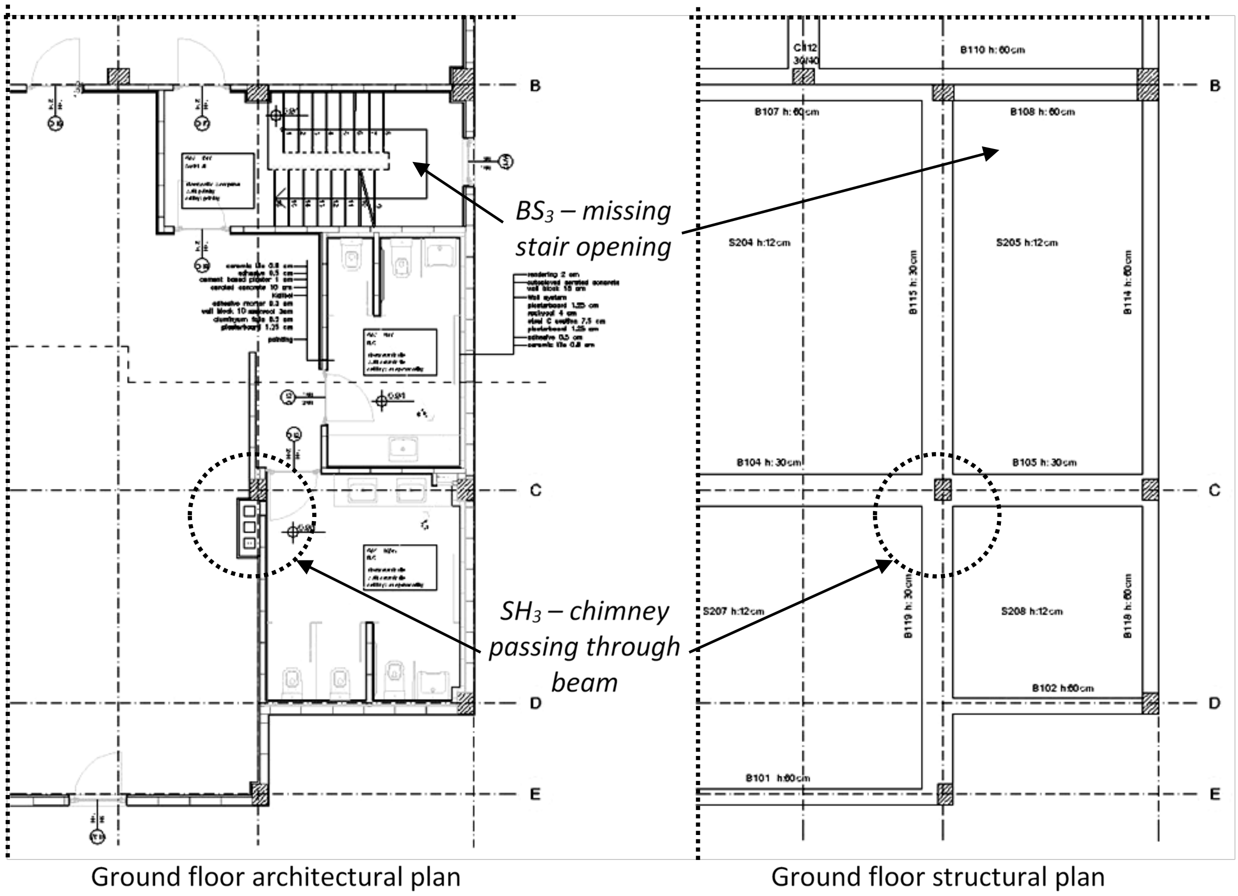

Figure 5: *Example of BS_3 and SH_3.*

were also remote from other architectural elements and thus called errors.

The problem observed in structural drawings was the missing stair or gallery opening (BS_3) with *meshed* interaction. It was called a *hard clash* considering the possible construction delays, when remained unnoticed (Figure 5).

On the whole, errors were the most common, followed by hard and soft clashes respectively. Among these, hard clashes are important concerning their effects on construction time and budget, and most hard clashes were related to the architects' coordination responsibility (BS_3), while cases directly related to architects' design responsibility were fewer. The type classification was also observed to be in line with the professionals' view on their significance, where the response average was the highest in BS_3 causing hard clash always, while it was the lowest in BS_2 causing soft clash sometimes, but without any effect most of the time (i.e. error). The average found for BS_1 causing a hard clash sometimes was between the other two.

3.2.2. Architectural and plumbing systems' integration

The most common problem in architectural drawings was missing or wrong positioning of vertical services shafts (BP_1). To decide whether they were soft or hard clashes, necessary spatial layout changes were considered, and some of them were observed to not affect inter-space organisation or organisation within the space (Figure 6-A), while others could be avoided by rearranging a limited number of components within that space such as sink or toilet (Figure 6-B). Thus, they were all called soft clashes.

Insufficient wall thickness to embed reservoirs, water supply pipes or drains (BP_2) was the second most common problem. Evaluation of the effect of constructing a second leaf to create the necessary gap for the pipes and drains showed that integrating a second leaf without changing the inter-space organisation was possible in all projects (Figure 7-A). Thus, they were all called errors.

Insufficient suspended ceiling depth to pass drains (BP_3) was the third common problem and to decide whether it would cause a soft or hard clash, the possibility of increasing the depth without changing any other element was evaluated. In the project where that was possible, it was called soft clash, but the one without that possibility due to the room height limitation was called hard clash.

The least common problem was the vertical services shaft blocking a window or door (BP_4). Construction phases and the possibility of changing window/door position were evaluated, and the blocked window within a reinforced concrete shear wall (Figure 7-B) was called a hard clash since its place could not be altered when noticed after shear wall construction. The blocked door in a brick infill wall, whose repositioning was possible without

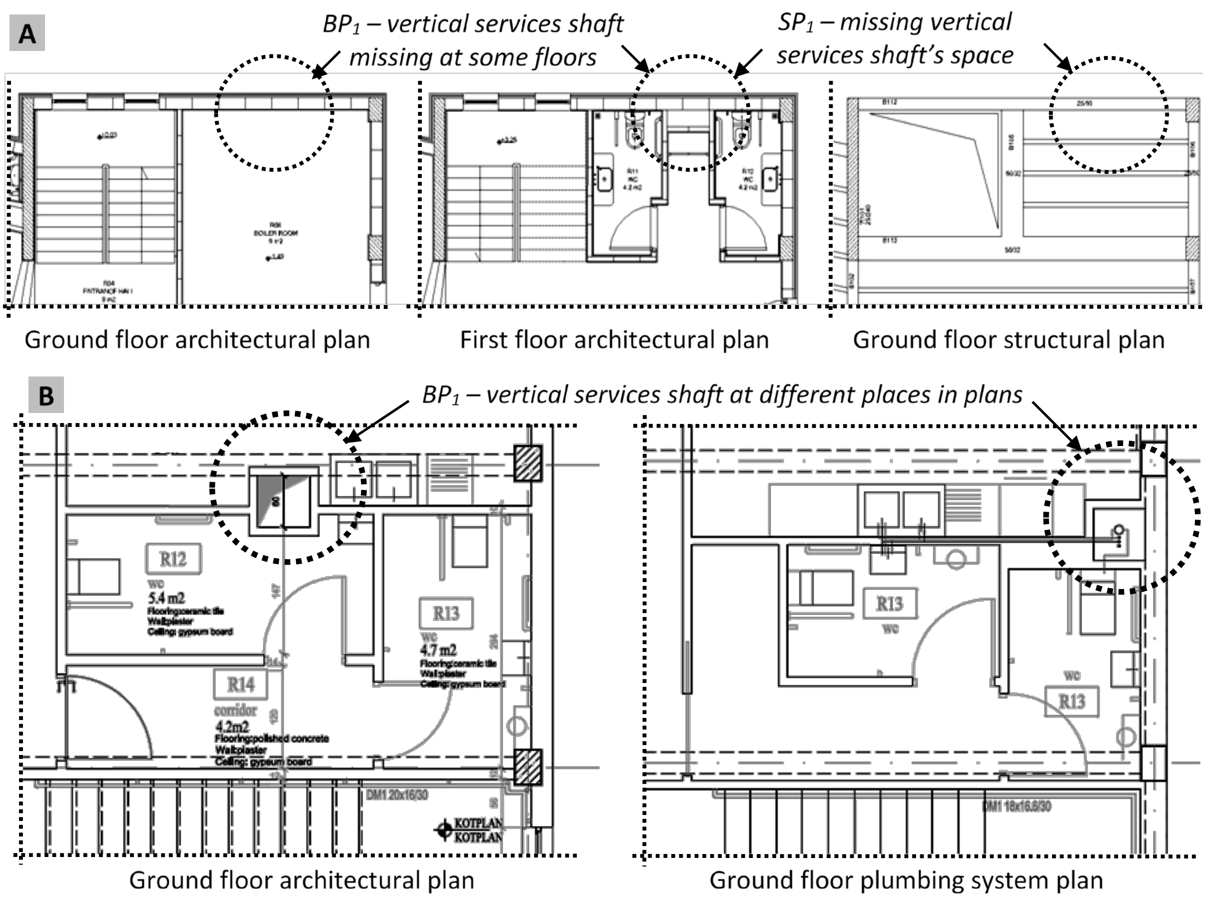

Figure 6: *Examples of BP_1 and SP_1.*

a need for rearranging the interior space, was called a soft clash since the clash problem would most likely be noticed before wall construction.

On the whole, soft clash was the most common, followed respectively by error and hard clash. Soft clashes and errors were observed always at meshed components, while hard clashes were observed, as expected, at systems/components that need to be remote. Additionally, all integration problems listed were directly under the architect's design responsibility, except for BP_4 which could be due to a lack of coordination with the plumbing system designer.

Professionals' opinions on their significance were not in line with the classification, most likely because of the lack of sufficient space in their previous experiences for the necessary rearrangement to avoid the hard clash. In the course, economic issues related to space use were not a design priority, while it is in real-life projects. Therefore, situations observed in students' projects were not as significant as professionals decided considering their previous experiences.

3.2.3. Architectural and heating systems' integration

The problems observed in architectural drawings were mostly related to the underfloor heating system. Tubes passing underneath masonry walls or at floor-stair connection (BH_1) were called soft clash, considering construction stages. Tubes passing under stud walls instead of openings (BH_2) were called

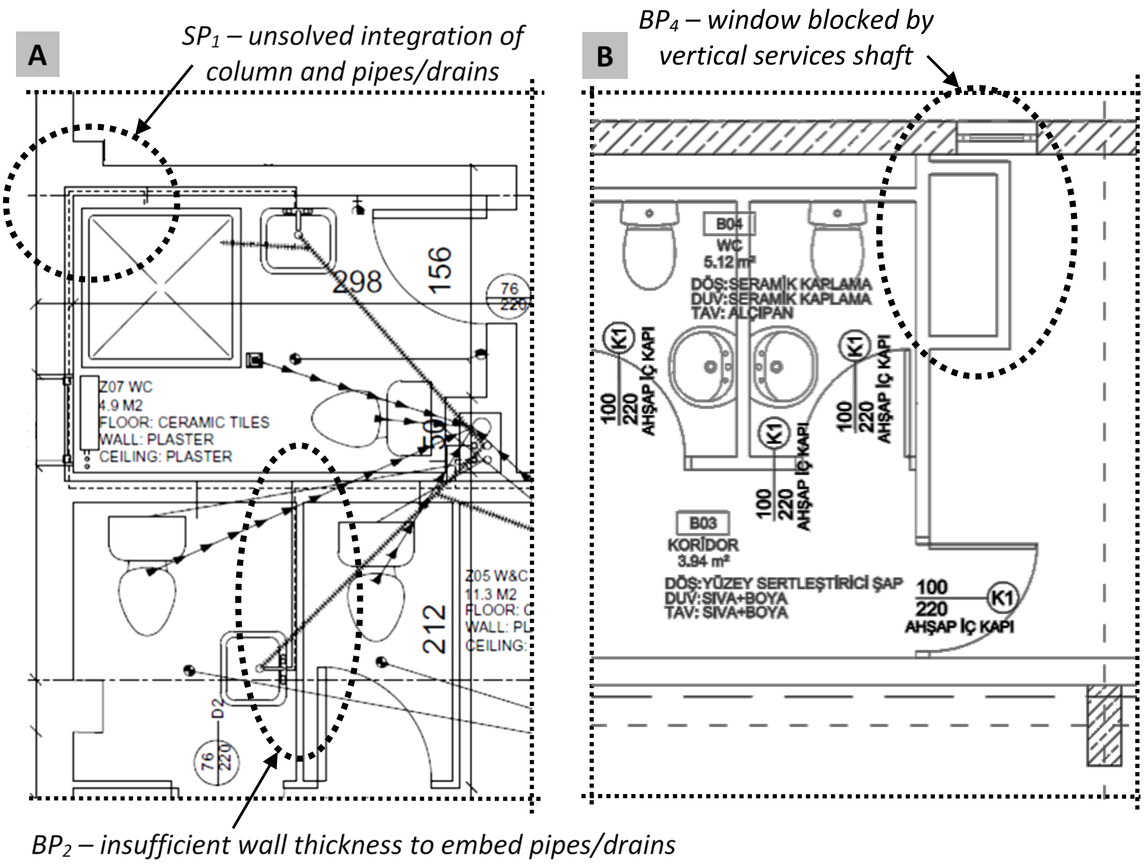

Figure 7: *Examples of (A) BP_2, SP_1 and (B) BP_4.*

hard clash since damaging them while fixing the stud wall's base channel was a possibility. The missing/insufficient underfloor heating system layer in the architectural section (BH_3) was called soft clash since the storey height allowed its correction by increasing screed thickness even when noticed during construction. The last problem, the missing chimney in the architectural plan (BH_4) was seen only in a single floor plan of a project, and it did not cause a redesign need regarding the inter-space organisation when constructed as it should be. Therefore, it was called a soft clash.

On the whole, soft clashes were the commonest with one hard clash only and no errors. It was also noticed that, in systems that need to be remote, both soft and hard clashes can be possible due to the effects of construction sequence and technology preferred, such as observed with BH_2 and BH_4.

Regarding professionals' views, the most significant problem was BH_4, followed respectively by BH_1, BH_3, and BH_2. Among them, type classifications of BH_2 and BH_4 were not in line with professionals' opinions; where a hard clash decision took the lowest point, and a soft clash decision took the highest. The most likely reason regarding BH_4 might be again the space use freedom of students in terms of economic issues. Concerning BH_2, the risk of damaging tubes could be considered low by the professionals as it was explained to be in an isolated area in the survey.

3.2.4. Structural and plumbing systems' integration

The omitted vertical services shaft reservations at structural plans (SP_1) were the most common problem (Figure 6-A). It was called a hard clash considering the likely redesign necessity structurally. The second most common problem was the unsolved integration of

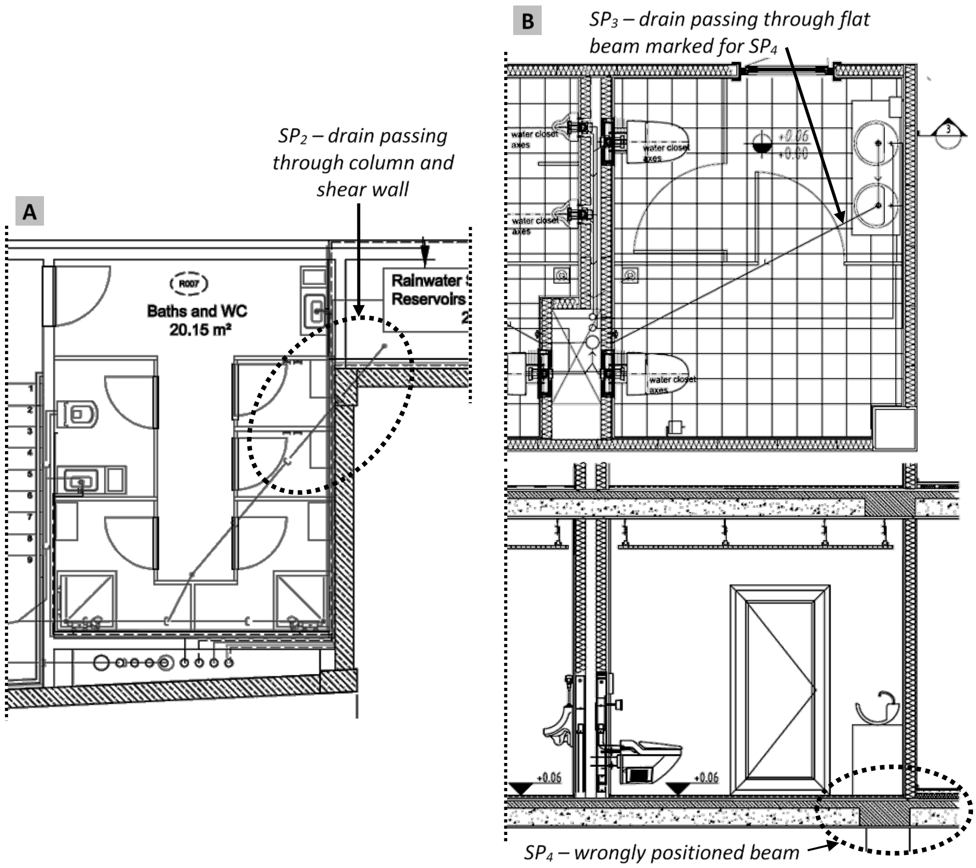

Figure 8: *Examples of (A) SP_2 with hard clash, and (B) SP_3 and SP_4.*

columns/loadbearing walls and horizontal supply pipes/drains (SP_2) in 1/50 plumbing system drawings. Cases with horizontal pipes passing through structural elements were called hard clashes (Figure 7-A and Figure 8-A). Cases with pipes passing in front of structural members without a solution to hide them were called omissions since exposing pipes or drains is not a common practice in Turkey. Supply pipes/drains or services shaft passing through a beam (SP3) was the least common problem (Figure 5 and 8-B) and called hard clash.

In half of the projects with relevant drawings, some beams were either missing or wrongly located or some additional beams were included in 1/20 sanitary area sections (SP_4). An additional beam seen in one project was directly called an error. The wrongly positioned beams seen in three projects would still be remote from pipes/drains when positioned correctly and were therefore called errors. The missing beams seen in five projects, on the other hand, which would again be remote from sanitary components when included properly, were called omissions.

On the whole, hard clashes were the most common, followed by omission, and error respectively. Among the hard clashes, 59% of the cases were related to the architect's control/coordination responsibility (i.e. SP_1). Structural drawings were made before designing services systems, and missing the revision necessity for the final submission was the most likely reason for SP_1. Regarding the architects' design responsibility, unintended meshed connections with the beam were four times more than that of columns/loadbearing walls, showing that drawing students' attention to evaluate the situation in section view is a necessity.

Regarding professionals' views, the two problems decided to cause a hard clash always (i.e. SP_1 and SP_3) had the two highest averages. Therefore, type classification was in line with opinions. However, in SP_2 with a couple of hard clash problems, the opinions were not in line with the classification, and it had the lowest average. Yet, in the survey question, only the unsolved integration was asked without mentioning that pipes are passing through structural members, and this might be the reason for the difference. Regarding SP_4, the relatively high point of 4.71 was not in line with classification without any apparent possible reason and can be questioned in further studies.

3.2.5. Structural and heating systems' integration

Missing openings at structural slabs for the heating system vertical pipes (SH_1) and the chimney (SH_2) in structural system drawings, and a chimney or a vertical heating system pipe that would pass through a beam (SH_3) were the three problems observed. The most common problem SH_1 was directly called soft clash, considering that the opening for pipes is small and can be done after structural slab construction. SH_2 was called a hard clash since it has to be considered during structural design due to its larger size. Regarding the least common problem SH_3, there is a possibility of diverting the vertical heating system pipes around the beams during installation without affecting the interior space much, unless it is a flat beam. Therefore, the former situation was called a soft clash, while the latter situation concerning the flat beam was called a hard clash. This kind of diversion is not possible for the chimney as well, and thus it was called hard clash too.

On the whole, soft clashes were more common than hard clashes, and all of them were related to the architect's control/coordination responsibility. Considering these, it can be said that most students gained the necessary insight to avoid time-csonsuming and cost-increasing hard clashes.

Regarding professionals' opinions, problems related to chimneys causing hard clashes (i.e. SH_3 and SH_2) had high average points, while the one concerning vertical heating system pipes only and causing a soft clash had the lowest. Therefore, it can be said that type classification was in line with professionals' opinions to a great extent.

3.2.6. Plumbing and heating systems' integration

The two problems observed were the underfloor heating tubes passing under the toilet with an 'S' trap (PH_1) and the overlapping or too close main distribution pipes (PH_2). In PH_1, unintended meshed relation can be noticed before installing underfloor heating system components, and tubes can be rerouted to avoid a clash. In the case given in Figure 9 for instance, the sanitary area was over slab-on-grade, and since wastewater drains should be placed before lean concrete, clashes could be noticed before placing heating system tubes. Considering this rerouting possibility, PH_1 was therefore called a soft clash. Regarding PH_2, a more common problem, the space availability to reroute them during installation without changing inter-space organisation was evaluated, and as necessary space was available in all projects, they were called soft clashes. On the whole, considering that there were no hard clashes and both problems were within the architect's control/coordination responsibility, it can be said that most students gained the necessary insight to avoid clashes. Regarding professionals' opinions, the response averages for these problems, both of which were called soft clashes, were close to each other. Therefore, type classification can be considered to be in line with their opinions.

3.2.7. Comparative discussion of integration problem review

Points coming forward regarding the total count and average of each integration problem type observed at each system pair and pairs' interaction types given in Table 4 are as follows:

- Among pairs, the highest occurrence rate was in BS, followed respectively by SH and SP, where the structural system (S) was taking place in all. Concerning the architect's responsibility in these, the cumulative sums of projects containing problems regarding the architects' design

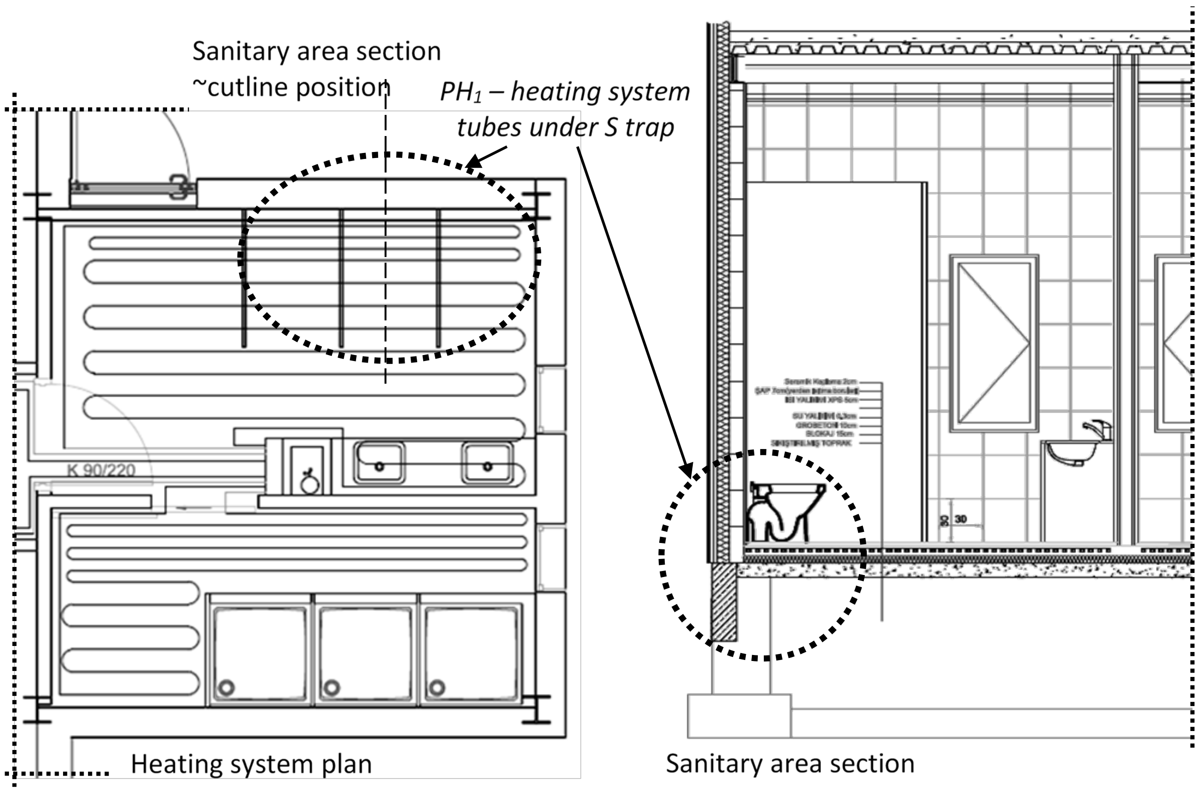

Figure 9: *Example of PH_1.*

duty and control/coordination duty were equal to each other (i.e. 49 in both). The latter shows that students' attention needs to be drawn to the structural systems' importance in producing problem-free projects, in connection with gaining experience in their control/coordination duty in professional life. Regarding architects' design duty, most problems were observed at BS, but within those, errors with less effect on construction time and budget were the commonest. However, as these errors may also cause confusion during construction, it shows that students' attention needs to be drawn to the precision of drawings.

- The occurrence rates in BP and BH were the smallest; 25% and 16% respectively, and nearly all of them were directly within the architect's design duty. These relatively lower occurrence rates show that students gained adequate experience in integrating these disciplines' information/knowledge into their designs.
- NAAB-SPC expects an ability to make proper design decisions regarding the integration and consideration of environmental systems, structural systems, and building envelope systems and assemblies, among others (NAAB, 2019). The total problem count in each project ranged between 2 and 10, and the average was 6.1. The number of problem-free projects in each pair ranged between 1 and 3. When these figures are considered together, problems can be said to be almost homogeneously distributed to the projects. Therefore, considering also the occurrence rate of 43% concerning all pairs together, it can be said that students were successful in the integration of most systems.
- Regarding the components' ordinary interaction, remote and meshed relations were considerably more common than

Table 4: *Overview of interaction types within pairs with deficiency and of integration problem types.*

Pairs	PFP	ΣCP_T	IT	Σ IT	Av. %	E		O		C_S		C_H		$E+O+C_S+C_H$	
						ΣCP_I	OR - %	ΣCP_I	OR - %	ΣCP_I	OR - %	ΣCP_I	OR - %	ΣCP_I	OR - %
			R	18	47	18		0		0		0			
BS	3	59	T	11	29	4	34	0	0	4	7	3	20	34	58
			M	9	24	0		0		0		9			
			R	4	23	0		0		2		2			
BP	3	67	T	0	0	-	8	-	0	-	15	-	3	17	25
			M	13	77	5		0		8		0			
			R	3	60	0		0		2		1			
BH	1	31	T	1	20	0	0	0	0	1	13	0	3	5	16
			M	1	20	0		0		1		0			
			R	24	65	4		11		0		10			
SP	1	72	T	0	0	-	6	-	15	-	0	-	32	37*	51
			M	13	35	0		0		0		13			
			R	4	21	0		0		2		2			
SH	2	36	T	0	0	-	0	-	0	-	34	-	16	19	53
			M	15	79	0		0		11		4			
			R	6	100	0		0		6		0			
PH	1	16	T	0	0	-	0	-	0	-	100	-	0	6	38
			M	0	0	-		-		-		-			
			R	59	48	22		11		12		15			
WP	0	281	T	12	10	4	11	0	4	5	13	3	16	122*	43
			M	51	42	5		0		20		26			

PFP: Problem-free projects **ΣCP_T:** Cumulative sum of CP_T **E:** Error **O:** Omission **C_S:** Soft clash **C_H:** Hard clash
IT: Interaction type **Σ IT:** Cumulative sum of problems observed at each IT **Av.:** Average of Σ IT
ΣCP_I: Cumulative sum of CP_I **OR (Occurrence Rate):** ΣCP_I / ΣCP_T in per cent
R: Remote **T:** Touching **M:** Meshed **WP:** Whole pairs
***:** In one project, there were two different kinds of interaction problems regarding SP_4, and therefore, the sum of deficiencies is different from ΣCP_I.

touching relations. The large problem count occurring due to unintended meshed connections between the components that need to be remote is an expected situation. However, the large problem count observed in meshed relations shows that students' attention needs to be drawn more to integration issues in meshed systems/components.

- Among different types of integration problems, the omission was the least common with an occurrence rate of 4%, while that of error, soft and hard clash were higher and close to each other (i.e. between 11% and 16%). Among these, the hard clash has a major effect on construction time and budget, and although it was the most common, the figure was still small, and therefore it can be said that students produced nearly hard clash-free projects.

4. Concluding remarks

Building is a complex system composed of different subsystems with different professions involved in its design. Within this complex process due to various actors, architects, in addition to their design duties, have to direct and coordinate other parties for a properly integrated design solution that will not cause rework and in turn time and budget increase. To this end, students of ITU-DoA practice subsystem integration in the Construction Project course by designing and detailing a small-sized building.

In the article, evaluations performed on 20 final submissions for this course are presented. The main objective was to determine and discuss the design deficiencies and subsystem integration problems. For this purpose, structural, heating and plumbing systems drawings were examined first to determine design deficiencies, classified into two groups; error and omission. Architectural drawings together with the aforementioned ones were then comparatively reviewed in pairs to determine integration problems, classified into four groups; error, omission, and soft and hard clash. Concerning these integration problems, the ordinary interaction between the components was also examined using four interaction types; remote, touching, meshed and unified. Additionally, the opinions of a few professionals on the significance of these integration problems in causing rework were considered while discussing classifications. The following observations were made and concluding remarks were drawn from these evaluations and discussions.

Concerning the design deficiencies;

- In total, 12 deficiencies were identified; five regarding the plumbing system, four regarding the structural system, and three regarding the heating system. Most of them were omissions, such as a missing chimney, rather than errors, like a discrepancy between a plan and its section. However, as a pattern that was found to be similar to those in real-life projects, the occurrence rate of errors in the projects was higher than omissions'.
- The students were more successful in structural system design. Yet, it was observed that the deficiency-free project count in plumbing and heating systems designs could be increased considerably by focusing more on two particular problems.

Concerning the integration within system pairs;

- In total, 20 integration problems were identified. In system pairs with a high occurrence rate of integration problems (i.e. OR >50%), the structural system was always a component of these pairs, although the occurrence rate of design deficiency was the lowest in that system. The cumulative sums of projects containing problems regarding architects' design and control/coordination duties were equal, and errors were the commonest cause of the former. Concerning the latter duty, according to professionals, almost all problems have a very significant effect on construction rework (i.e. >4.5). To increase the number of problem-free projects, stressing more the importance of the structural system in coordination-related problems and the importance of architectural drawings' precision in design-related problems came forward as an educational strategy.

- Omission was the least common problem with a 4% occurrence rate, while those of error, and soft and hard clashes were just 7-12 points higher. Among these problems, professionals generally rated the problems causing hard clashes as having a very significant effect on construction time and budget (i.e. >4.5). Taking into account both, even the 16% occurrence rate of the hard clash can be accepted to be a sign of producing almost clash-free projects.
- Regarding the ordinary interaction between the components of system pairs, problems were more common in remote and meshed systems than in touching systems. Although the ones related to *remote* systems can be expected, those related to *meshed* systems showed that more attention must be drawn to the integration of plumbing and heating systems' meshed components.

Concerning the objectives of the course in general;

- The smaller rates of *omissions* observed in the design deficiency and integration reviews were accepted as a good sign of gaining the necessary experience in using the knowledge and principles related to structural, plumbing and heating systems in their projects.
- The occurrence rates of errors, and soft and hard clashes observed in the integration review were not too high; ranging between 11% and 16%. These figures were accepted to be a good indicator of gaining the necessary skills and experience in the integration of subsystems.

For future terms, apart from the aforementioned issues, the deficiency and integration problems lists are planned to be prepared as a checklist that can be used in the final submissions. Improvements achieved by using these strategies together with a broader survey among professionals and assessment of integrating effective BIM use in the course can be a subject of future research.

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