The Temporary Timber Roof
A quantitative design approach

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Abstract

This paper is part of a graduation project at the faculty of Architecture at the University of Delft. The scope of the project is the design of a temporary community centre at a central square, Piazza del Duomo, in the earthquake-damaged historical town of L'Aquila, Italy. It will consist of a timber roof structure with closed and structurally independent volumes underneath.

As the architectural design will be temporary and its surrounding building stock is heavily damaged, the design of the roofing structure has few boundaries and the possibilities are infinite. This research aims at creating order in the chaos of possibilities through quantitative analysis.

Models are formulated through variations in four different fields: six different structure types, four different spans, three different core-to-core distances and three different heights. Five of their characteristics are quantified and graded systematically in order to compare them: earthquake-safety; spaciousness; functional flexibility; structural flexibility; and structural modesty.

After careful interpretation of the results during a step-by-step elimination process, two models remain: both have the same span, the same core-to-core distances and the same height, but their typology is diffent. The first outcome has relatively short structural elements, causing a high score for structural flexibility. The second outcome has an efficient curved shape, ranking high on structural modesty.

This quantitive analysis results in a conceptual framework for the further design process: a timber roof consisting of three spans over the width of the Piazza del Duomo, a relatively small core-to-core distance and a spacious height, and a curved shape detailed with short structural elements.

Content

1 INTRODUCTION

This research paper is part of a graduation project in the studio Architectural Engineering at the University of Technology in Delft. In order to understand the context and the approach of this research, the actual graduation project will be explained, followed by the goal of this research and the build-up of this paper.

1.1 Background

The context of the graduation project is the city of L'Aquila in central Italy. On April 6, 2009, this town and its surrounding area were heavily struck by an earthquake of around magnitude 6.0. Though the earthquake was only a medium-power event, the consequences were disproportionally large: more than 300 people died, around 1,500 people were injured and more than 65,000 people were rendered homeless. The historic town centre of L'Aquila was among the heaviest damaged areas and though it has been almost eight years since the occurrence, the city centre is still a ghost town (Agnew, 2016).

In an in-depth study of the redevelopment after the L'Aquila earthquake and the associated governmental policies, Alexander (2010) brings forward one of the biggest underlying problems for this lengthy process: the missing element in the Italian Government's recovery policy was local participation, the citizens were not heard. This led to much discontent and a decline in local economy, eventually resulting in a peaceful demonstration. But all was ignored by the government (Alexander, 2010). The focus has been on decentralized short-term solutions only, and the locals feel as if they have been forgotten and they have no reason to return to their centre, even though they want to.

The graduation project, which is called *Opportunity in Chaos*, provides an alternative after-earthquake approach. The general goal is to design a temporary and multipurpose community centre in the middle of the historic town of L'Aquila, at the big central square called Piazza del Duomo, which has always been the cultural and social centre of the town. The community centre forms a platform for discussion between and all-round participation of all relevant parties in the recovery process, to ensure sustainable redevelopment. Another object of the architectural intervention is to give people a reason to visit their town centre during the recovery process and to provide them with a pleasant and spacious place for social and cultural activities. The basic design will consists over a roofing structure over the Piazza underneath which a closed volume with a floor area of around 300 m^2 will be placed.

The aspirations of this project are quite paradoxical. The design needs to be flexible in use which requires as much open space as possible which would imply the use large structural elements. Simultaneously, structural flexibility is required in order to be easy-to-assemble and reusable in different contexts, which would mean the elements should be as small as possible. On top of these demands, the community centre should create a pleasant and welcoming environment, future earthquakes should be resisted sufficiently and the neighbouring architecture should be taken into account.

Multiple researches have been carried out to confirm the psychological and physiological benefits of wood and daylight, both outdoors and in interior design (Rice, 2004; Song & Fei, 2016). Thus, the design will primarily be constructed in timber and designed with plenty of daylight. Steel is the secondary material, which will be used for joinery and stabilisation.

1.2 Research goal

As neither the context nor the program provide any clear architectural limitations, the options are limitless. On the one hand, this gives a lot of architectural freedom; on the other hand, there is nowhere to start. The goal of this research is to provide a well-founded conceptual framework to give the design process a kick-start. To do so, the following research question has been formulated:

"How can a conceptual framework be specified using quantitative analysis for a light and temporary timber roof structure at the Piazza del Duomo in the earthquake-prone city of L'Aquila, Italy?"

1.3 Content of the paper

First, the research method, quantitative research-by-design, is discussed. The input in the form of models, their quantification and the grading system will be elaborated. Second, the results will be shown in-depth, during a step-by-step elimination of models until finally the remaining models are presented. The results will be followed by a discussion reflecting upon the carried-out research and finally a conclusion to end the research. References and an appendix have been added to the paper.

2 Research method

The method chosen to investigate the matter at hand is quantitative research-by-design. For this method a large number of models will be researched quantitatively and how this will been done is described in this paragraph. The variable input for these models will be discussed first. An important step follows: how have several aspects these models be quantified in order to compare them? Lastly, the way the output is generated will be presented.

2.1 Input

First, restrictions and variations within the vast amount of structural possibilities for the research are put in place.

2.1.1 Types of structure

The structures to be looked into are wooden portals. They are assumed to span the Piazza over its width (35,0 m), while they are placed subsequently in longitudinal direction (78,0 m). The six different portals that will be further investigated are shown in Figure 1 (TU Eindhoven).

1. Portal 1: a straight-forward construction with clamped columns and a beam on top with basic joints
2. Portal 2: similar to portal 1, but the joints are rigid and thus the columns do not need to be clamped
3. Portal 3: a kinked portal with a basic roof shape under an angle α and usually a hinge in the middle of the span
4. Portal 4: very similar to portal 3, but with curved kinks
5. Portal 5: portal with an arched span with either a camber of (a) F = L/7; or (b) F = L/5.

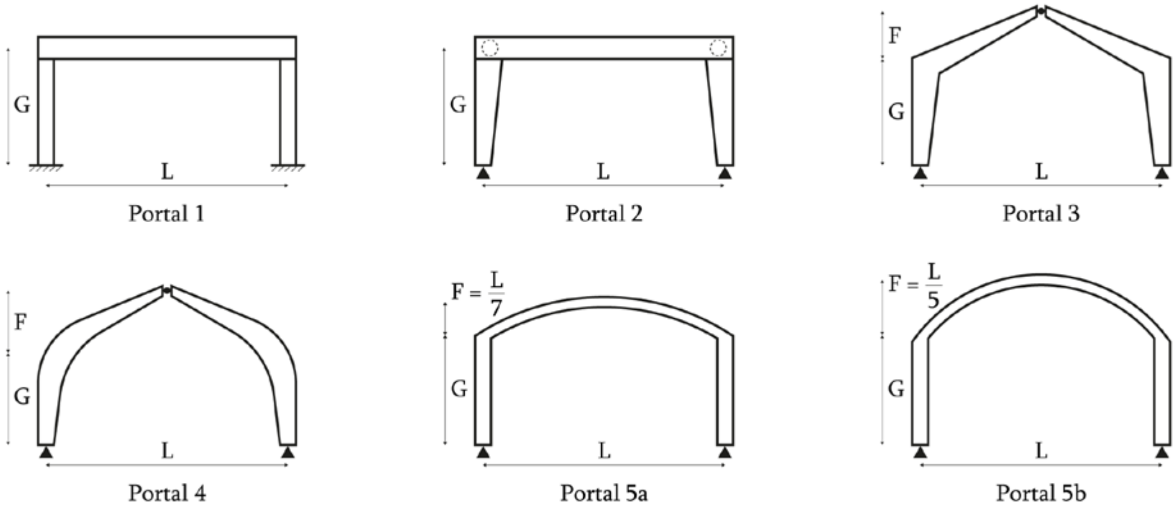

Figure 1 – Types of portals

2.1.2 Grids

The next step is to determine the grid variations on which these portals shall be placed.

Spans

The width of the Piazza is 35,0 m. This could be divided up into either one, two, three or four spans. Thus the possible spans L will be:

1. 35,0 m
2. 17,5 m
3. 11,7 m
4. 8,8 m

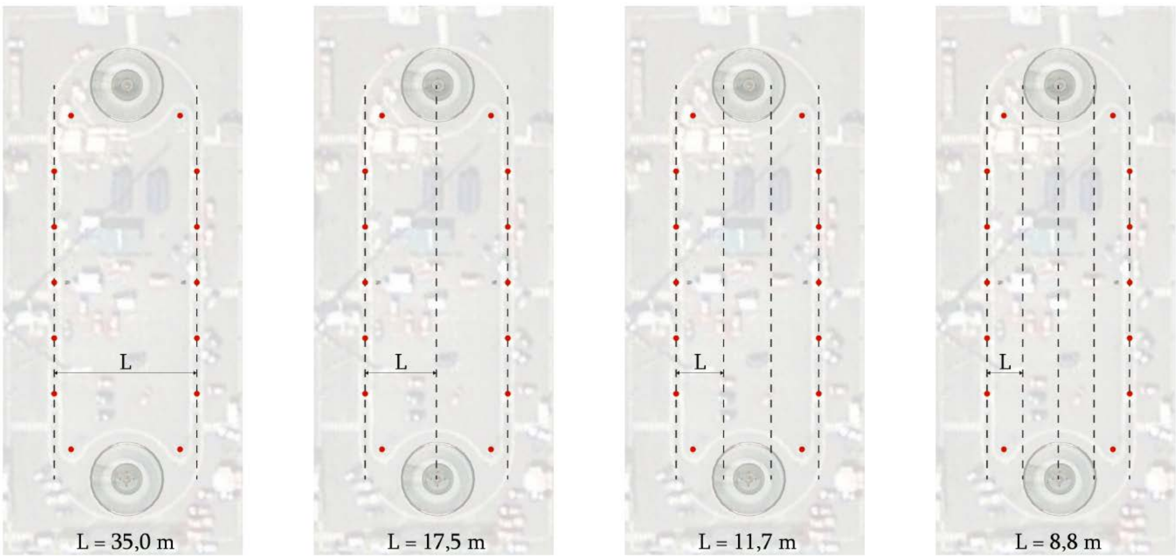

Figure 2 – Span variations

Core-to-core distances

The lampposts on the Piazza are a big part of its aesthetics and therefore, it has been chosen to take these into account in determining the grid in longitudinal direction. They are located approximately

13,0 m apart with the final ones placed a little more inward. As shown in Figure 3, the possibilities for the core-to-core distance comes down to:

1. 7,1 m
2. 6,5 m
3. 4,3 m

Figure 3 – Core-to-core variations

2.1.3 Structural heights

A few limitations have been set out for the height of the construction. First, the minimal height (H_{min}) is set to be 8,0 m in order to have enough free space to design a closed volume underneath. Second, the maximum height (H_{max}) is set at 16,0 m, similar to most of its neighbouring buildings.

Following these limits, the column height (G, see Figure 1) variations have been chosen at:

1. 8,0 m
2. 12,0 m
3. 16,0 m

As portals 3 to 5b would surpass the maximum height H_{max} if G is equal to 16,0 m due to their shape, they are excluded from this option, thus resulting in the variations as presented in Figure 4.

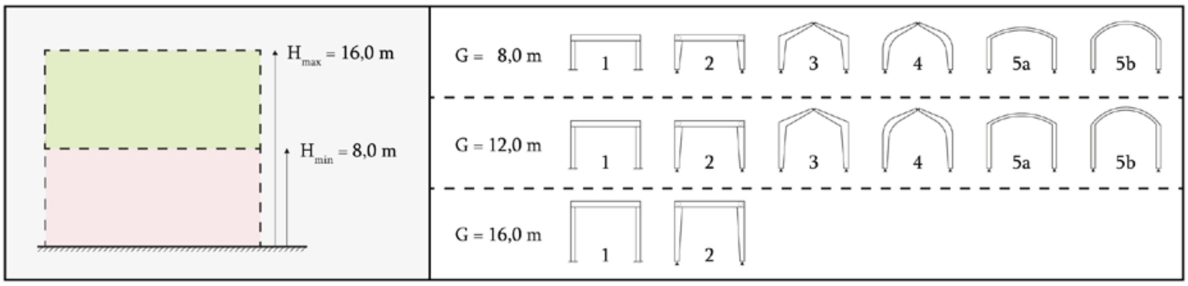

Figure 4 – Height variations

2.1.4 Rules of thumb

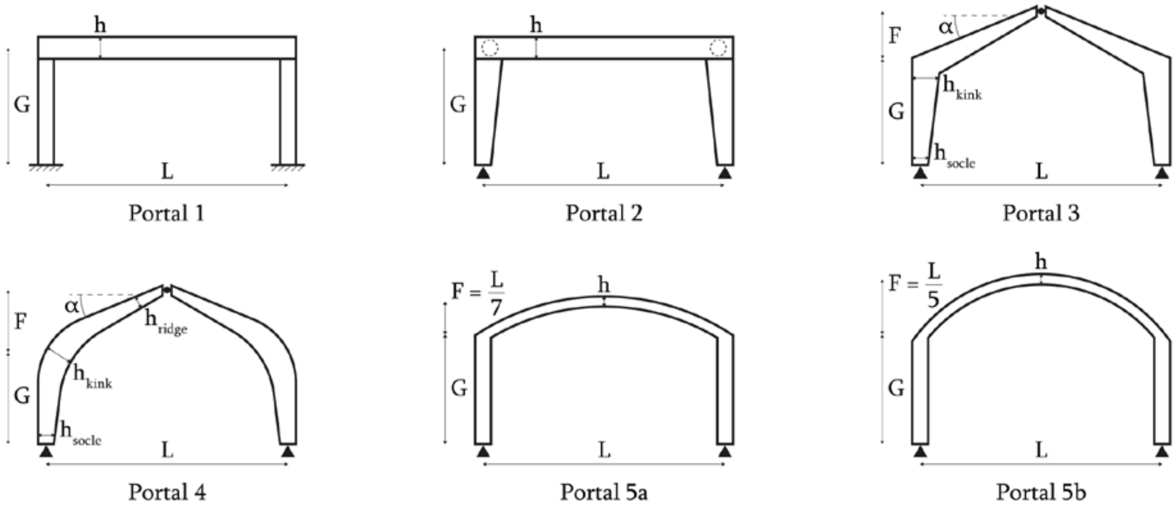

Figure 5 – Element sizes

For determining the elements sizes as presented in Figure 5, rules of thumb are used (TU Eindhoven).

Portal 1			c.t.c.: < 5 m	h = L/17
			c.t.c.: 5-8 m	h = L/16
Portal 2			c.t.c.: 4-8 m	h = L/15 à L/23
Portal 3		$\alpha = 20^\circ$	c.t.c.: 4-5 m	$h_{kink} = (L + G)/28$
				$h_{socle} = 0{,}40 \cdot h_{kink}$
			c.t.c.: 5-9 m	$h_{kink} = (L + G)/24$
				$h_{socle} = 0{,}40 \cdot h_{kink}$
Portal 4		$\alpha = 20^\circ$	c.t.c.: 4-5 m	$h_{kink} = (L + G)/31$
				$h_{ridge} = 0{,}50 \cdot h_{kink}$
				$h_{socle} = 0{,}67 \cdot h_{kink}$
			c.t.c.: 5-9 m	$h_{kink} = (L + G)/26$
				$h_{ridge} = 0{,}50 \cdot h_{kink}$
				$h_{socle} = 0{,}67 \cdot h_{kink}$
Portal 5	a	F = L/7	c.t.c.: < 5 m	h = L/45
			c.t.c.: 5-9 m	h = L/40
	b	F = L/5	c.t.c.: < 5 m	h = L/45
			c.t.c.: 5-9 m	h = L/40

2.1.5 Summary

In summary, the input will consist of:

i) Six different portal types
ii) Four different spans, *L*
iii) Three different core-to-core distances, *c.t.c.*
iv) Three different column heights, *G* (portal 3, 4, 5a and 5b are excluded from the third)

This results in 168 different models. To give an impression of all variable input, four of them are presented in Figure 6.

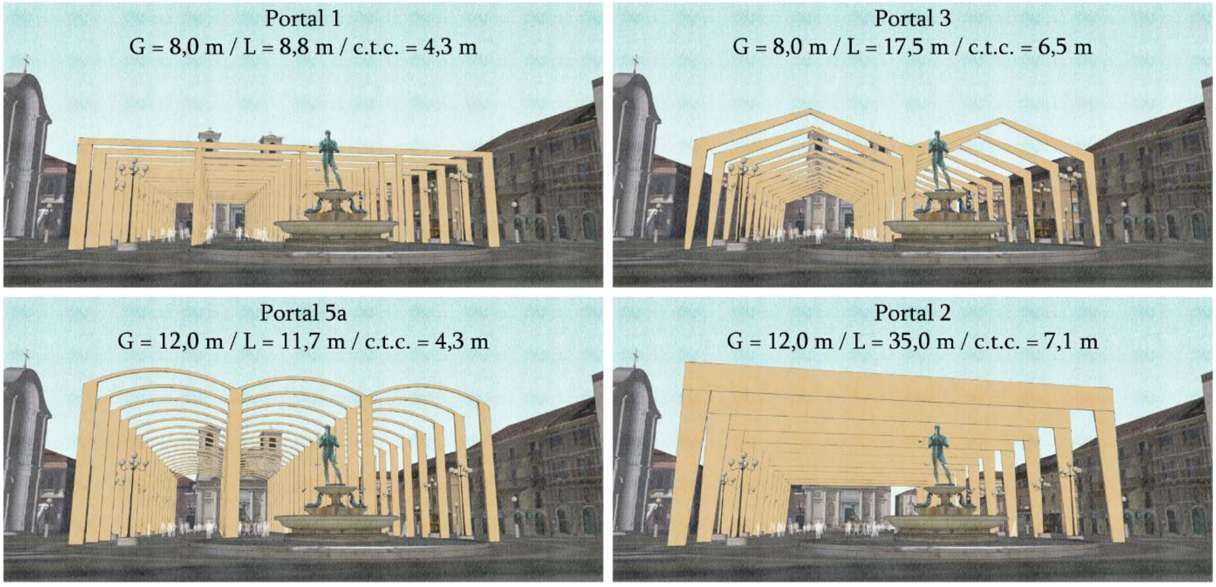

Figure 6 – Four impressions out of 168 models

2.2 Quantification

The next step is an important one in creating order in the chaos of all these models: the quantification of several of the models' characteristics. For this particular situation, five aspects will be assessed: (1) earthquake-safety; (2) spaciousness; (3) functional flexibility; (4) structural flexibility and (5) structural modesty. The way these aspects are translated into quantifiable data is explained below.

2.2.1 Earthquake-safety

This assessment criterion is major importance in the seismic area of central Italy: earthquake-safety. Earthquake-safety is dependent on multiple aspects: the scale of the structure, the way the joints are designed, the material, and so on. As this research is merely a first step in the design process, exact detailing does not play an important role yet. Therefore, the earthquake-safety criterion is expressed as the area of roof surface that will most likely fail in case one structural element – be it a beam or a column – collapses.

The failing roof area in case of a failing element is expressed as the span L multiplied by the core-to-core distance, as is graphically presented in Figure 7.

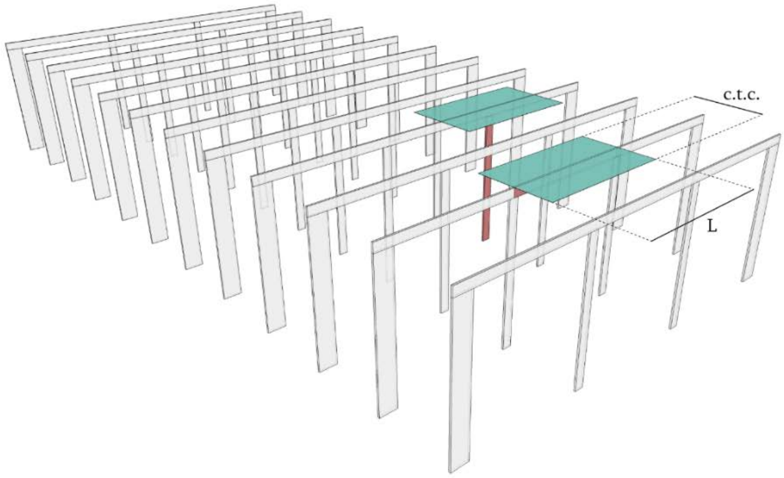

Figure 7 – Quantification of earthquake-safety [m²]

2.2.2 Spaciousness

The architectural experience of the construction should be airy, light and spacious in order to attract people to visit the town centre of L'Aquila. Though the experience of space may be a qualitative aspect, one could simplify the spaciousness quantatively as the maximum uninterrupted volume underneath the construction. This equals the cross-sectional area underneath the portal multiplied by the total length of the construction (set at 78,0 m), as it portrayed in Figure 8. Note that the dimensions of the structural elements have not been taken into account in calculating the volume.

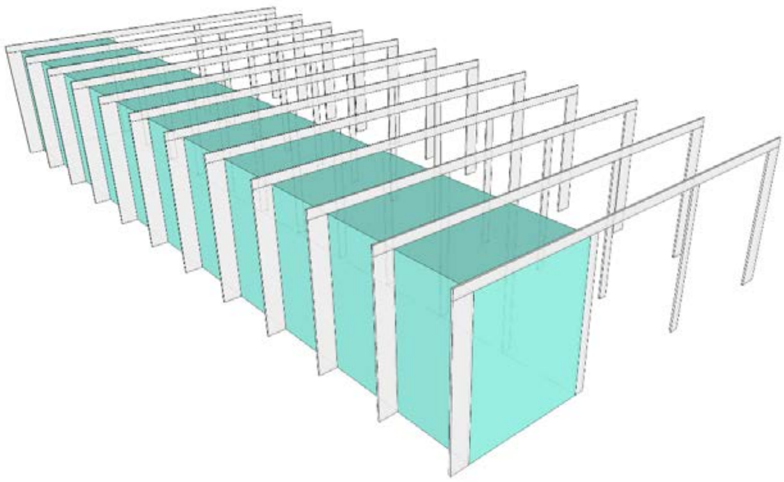

Figure 8 – Quantification of spaciousness [m³]

2.2.3 Functional flexibility

The new construction on the Piazza del Duomo has a broad program: it houses a multipurpose community centre and it provides a semi-outside space for several cultural and social activities. On top of this, the structure should be able to be reassembled at another location where the uses might differ. Therefore, the way the design is used should be flexible. This depends mostly on the uninterrupted free area underneath the structure, see Figure 9, which is directly linked to the span L. It has been chosen to express this variable in percentages, with 100% being a structure without any columns in the middle of the Piazza (and thus with L = 35,0 m). As well as for spaciousness, the sizes of the structural elements have been neglected in measuring the free area. Thus, the free area equals the span L multiplied by the total length of the structure (78,0 m).

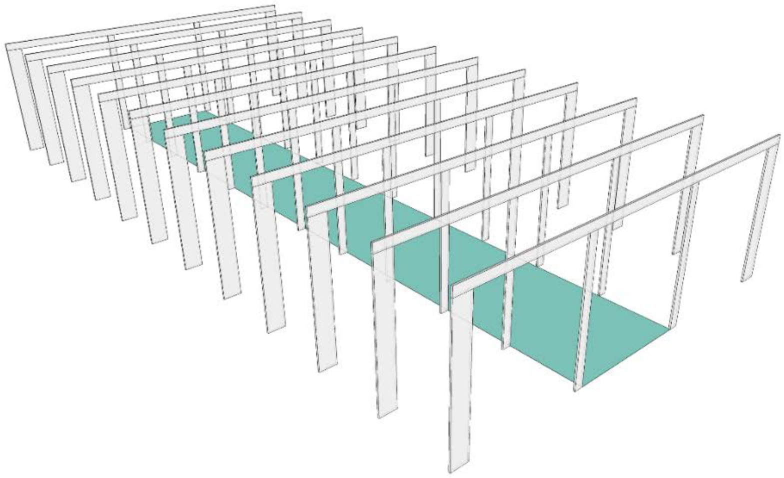

Figure 9 – Quantification of functional flexibility [%]

2.2.4 Structural flexibility

As the goal for the design is to be flexible for future uses in other locations, the structural flexibility is of significant importance; it should be able to adapt to other locations and other contextual shapes. The shorter the structural elements are, the easier it is to design something different. Thus, the structural flexibility is measured by the length of the portal beam elements, as presented in Figure 10. The lengths of curved or angled elements are calculated accordingly.

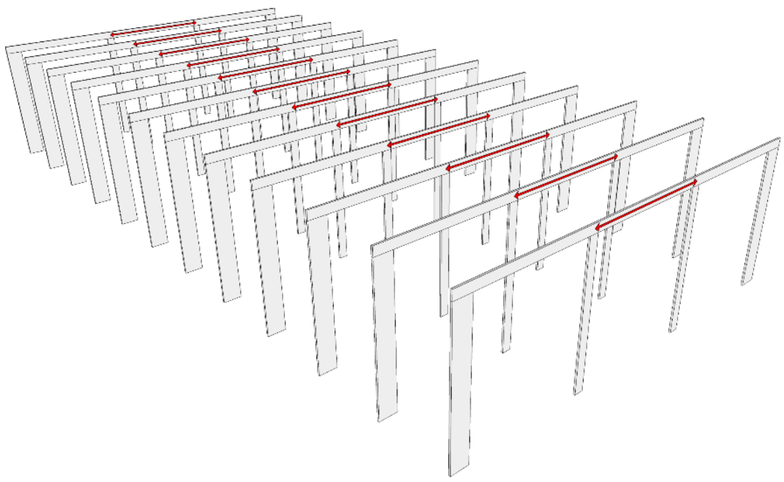

Figure 10 – Quantification of structural flexibility [m]

2.2.5 Structural modesty

Lastly, both from an architectural (light and airy) and a structural (easy-to-assemble) point of view, it is important the structural elements are not too massive. A main role in this is played by the size of the cross-sections of the structural elements. At this point in the design process, the height of the beams are calculated using rules of thumb as presented in paragraph 2.1.4. Thus, the average height of the beams – which are tapered in some cases – shall be used as a measuring unit.

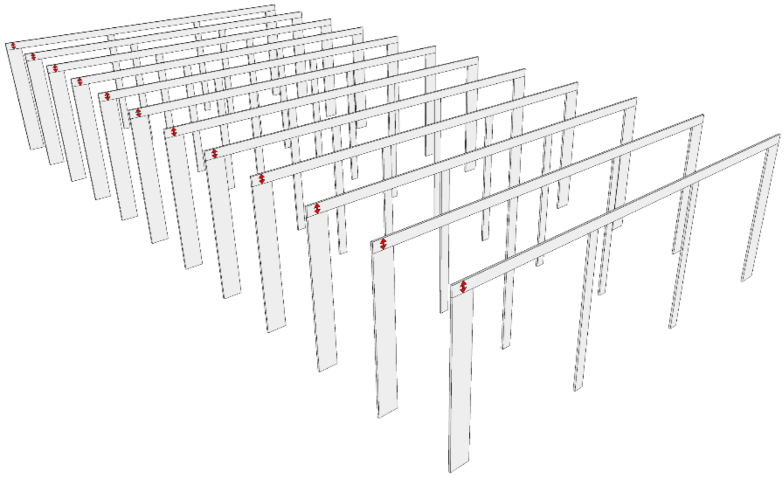

Figure 11 – Quantification of structural modesty [m]

2.3 Grading system

The next step in the research process is to assign scores to the quantified characteristics specified in the previous paragraph. The grades assigned will vary from a minimum of 1 (worst score possible) to a maximum of 10 (best score possible). The values used for the grading are extracted from the models produced, taking into account the maximum and minimum possible values. The exact grading is done by linear interpolation; values outside of the range are graded a minimum of 1 or a maximum of 10 accordingly.

2.3.1 Earthquake-safety [m²]

The earthquake-safety is measured by the roof area that would collapse, would one structural element fail. The smaller this area, the better.

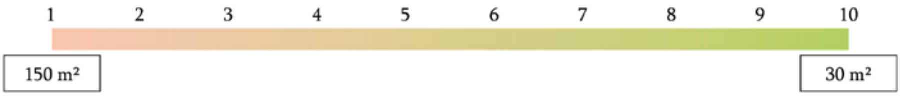

Figure 12 – Grading of earthquake-safety [m²]

2.3.2 Spaciousness [m³]

The spaciousness is quantified as the maximum uninterrupted volume underneath the structure. The goal is to make the design light and airy, and thus, bigger volumes get higher scores.

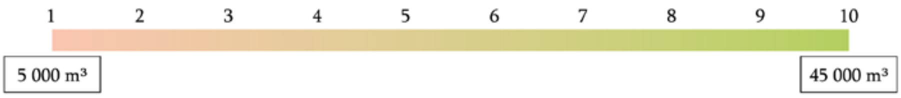

Figure 13 – Grading of spaciousness [m³]

2.3.3 Functional flexibility [%]

The functional flexibility is expressed by the percentage of uninterrupted ground area on the Piazza del Duomo. Self-explanatory, the higher this percentage, the better the structure scores.

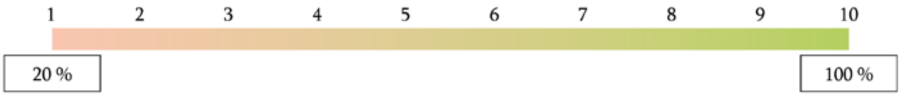

Figure 14 – Grading of functional flexibility [%]

2.3.4 Structural flexibility [m]

The criterion of structural flexibility is measured by the length of the spanning beams: the structure scores high if the length is short.

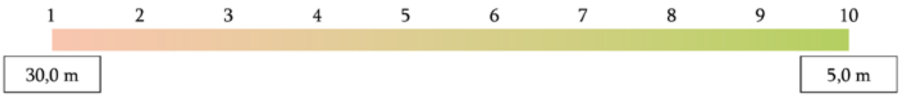

Figure 15 – Grading of structural flexibility [m]

2.3.5 Structural modesty [m]

Structural modesty is measured by the average height of the beams. The smaller the average beam height, the higher the score.

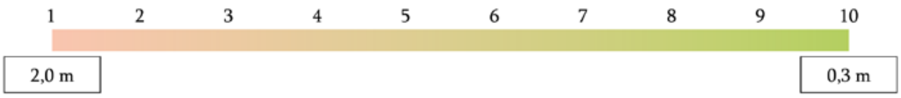

Figure 16 – Grading of structural modesty [m]

2.4 Output

The models will render grades for each assessment criterion, using the aforementioned linear interpolation. In combination, these grades will give a general score for each model through a weighted average. The next question is: how will these different criteria be weighted in order to provide proper research outcome?

The goal of this research is to do a fully quantitative assessment, as objective as possible. By prescribing a fixed weight to all formulated criteria, the outcome will be biased. So how will this research be conducted in order to get unbiased results?

First, all criteria will be weighted equally, ergo 1 : 1 : 1 : 1 : 1. This will give the best impression of which models score highest overall.

Next, five differently weighted calculations will be carried out one-by-one in which each of the criteria will be weighted 5. This will show which models will score high for that specific criterion. The other criteria are still playing a secondary, yet significant role: they will bring a hierarchy between the models that score the same for the emphasized criterion. In summary, the weighting will be 5 : 1 : 1 : 1 : 1 / 1 : 5 : 1 : 1 : 1 / 1 : 1 : 5 : 1 : 1 / 1 : 1 : 1 : 5 : 1 / 1 : 1 : 1 : 1 : 5.

Models will be eliminated from the pool of 168 variations during the selection process step-by-step. Slowly but surely the strongest ones will remain, providing a solid conceptual framework.

3 Results

Using the quantitative input, results have been generated. All the results generated are presented in Appendix: Scores. Three elimination steps are presented in the following paragraphs as well as the outcome: the two best designs within the pool of 168 models, according to this quantitative design approach.

*Number of models: **168***

3.1 Step-by-step elimination

3.1.1 First elimination round

Elimination of Portal 1

Quite quickly during the assessment, it became clear portal 1 would in no case be beneficial compared to portal 2. The shape of the structure is exactly the same, but as the joints in portal 1 are hinged, the height of the beams would be relatively high. One could argue portal 1 is easier to construct, as the joints do not need to be rigid. However, as shown in Figure 17, in case of portal 1 it is necessary to make a clamped foundation. This is relatively complicated and on top of that, it would be a very intrusive foundation for the Piazza del Duomo. Thus, all the models listed under the category Portal 1 are the first to be eliminated.

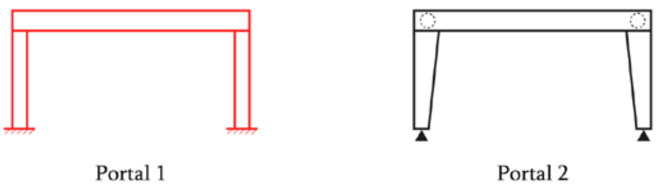

Figure 17 – First round: first elimination

*Number of models: **132***

Elimination of Portal 4

Another thing that became evident at an early stage in the research is the fact that Portal 3 and 4 are very similar, their results are practically the same. The difference between them is mostly aesthetical, and this could potentially be researched qualitatively during a following phase in the design process. However, Portal 4 serves no purpose during this quantitative research and is therefore the second group of portals to be eliminated.

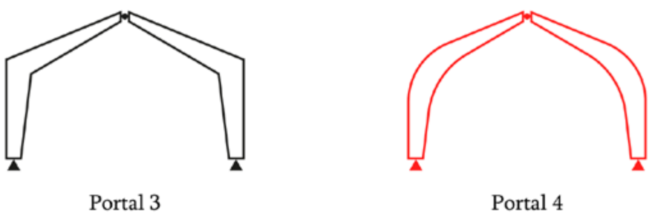

Figure 18 – First round: second elimination

*Number of models: **108***

3.1.2 Second elimination round

Elimination of portals with c.t.c. = 6,5/7,1 m

In Figure 19 all general outcomes of the remaining 108 models have been graphically presented. All models with a core-to-core distance of 4,3 m have a blue mark, while the ones with the higher core-to-core distances have been marked grey. It is clearly visible that overall the designs with the smallest core-to-core distance score significantly higher than the others.. One can imagine that structures with a smaller core-to-core distance are safer in earthquake-prone regions, as a smaller part will collapse in case of structural failure. This contributes mostly to this outcome.

This results in a big elimination in the remaining pool of structural models: all models with a core-to-core distance of 6,5 m or 7,1 m are eliminated and only 36 models remain.

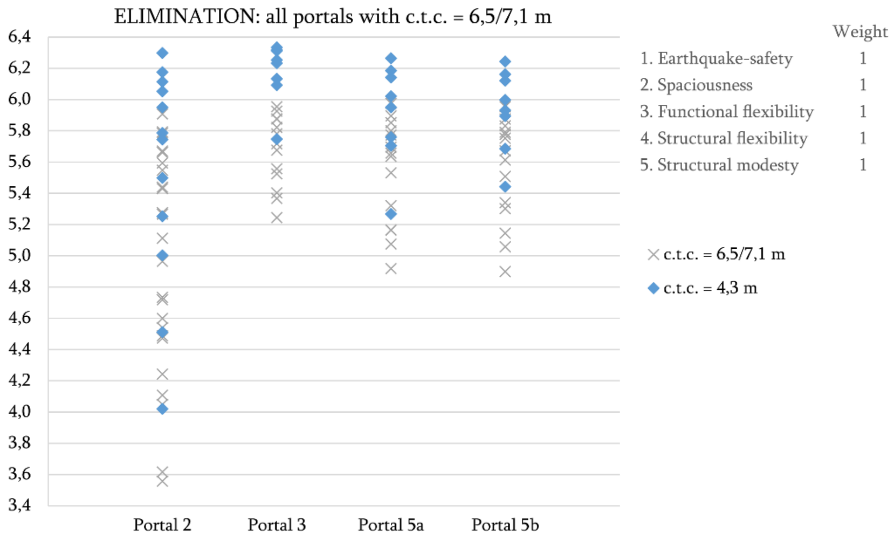

Figure 19 – Second round: first elimination

*Number of models: **36***

Elimination of "Portal 2" with G = 8,0 m

With only a core-to-core distance of 4,3 m remaining, a closer look at the Portal 2 category is taken. These are the only portals with three different height variations instead of two, as was explained in paragraph 2.1.3. In Figure 20, all results for Portal 2 are graphically presented under equal weighting. The designs with a column height of G = 8,0 m scores significantly lower than the other two for all spans. This can mostly be explained by the fact that the spaciousness – measured by the maximum uninterrupted volume – is much lower. The ones with a height of 12,0 m and 16,0 m are more comparable to the alternative portals with a column height of 8,0 m and 12,0 m respectively. Therefore, all portals under the category "Portal 2" with G = 8,0 m are eliminated and 32 models remain.

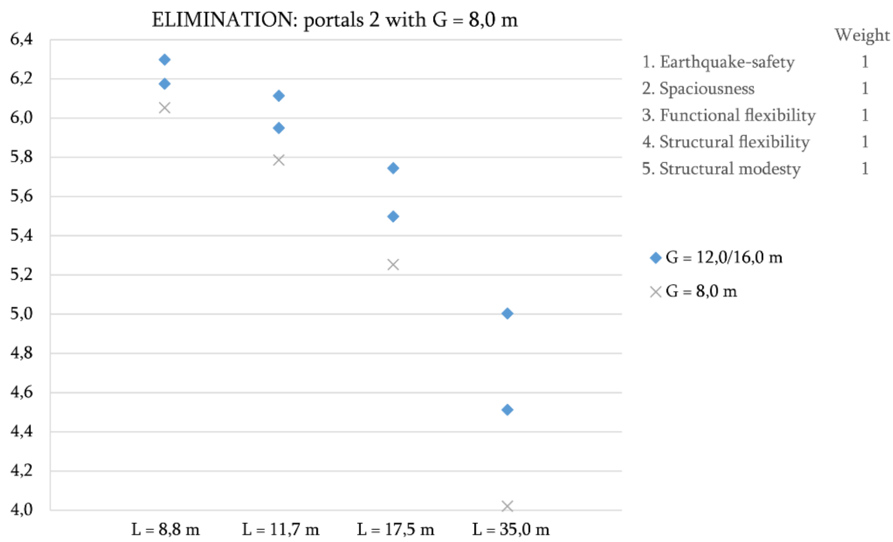

Figure 20 – Second round: second elimination

*Number of models: **32***

Elimination of portals with L = 8,8 m & 35,0 m

Looking at the scores with general weighting, it may not be clear why the next two groups of portals (those with a span of L = 8,8 m and L = 35,0 m) are eliminated, as they seem to score quite high. In this case, it is necessary to have a closer look at the calculation with unequal weighting. In Figure 21, the outcome has been presented with an emphasis on Functional Flexibility – which is measured by the percentage of uninterrupted Piazza-area. In Figure 22, the results are shown with an emphasis on Structural Flexibility – measured by the beam length.

As was to be expected in the case of Functional Flexibility, structures with the maximum span of L = 35,0 m score extremely high. However, these same structures have the lowest score in the case of Structural Flexibility, due to their huge structural elements. So even though the models with this large span have some very good scores, it is unacceptable they are graded this low in the other fields. Thus, all models with a span of L = 35,0 m are eliminated.

Exactly the same goes for the models with a span of L = 8,8 m. These designs show very high scores for Structural Flexibility, but their results in Functional Flexibility are unacceptably low. Therefore, all models with a span of L = 8,8 m are eliminated too and now, only 16 models remain.

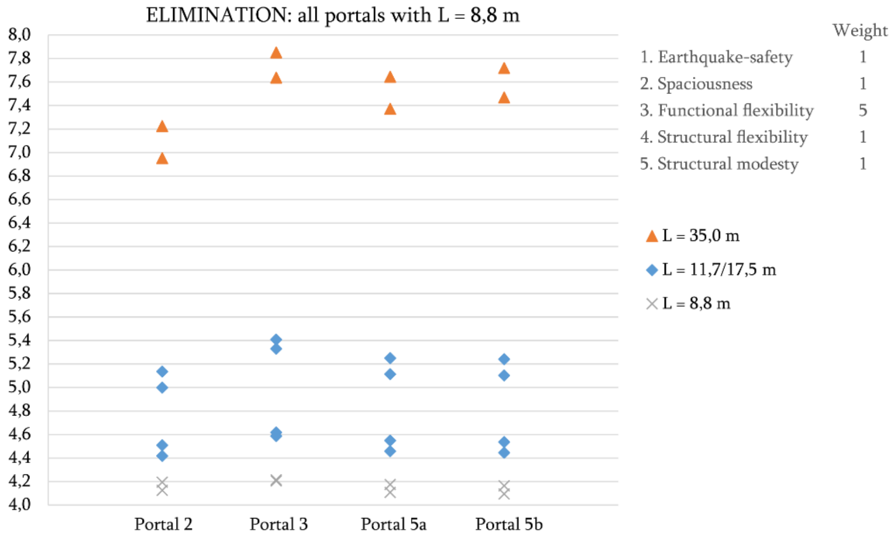

Figure 21 – Second round: third elimination (a)

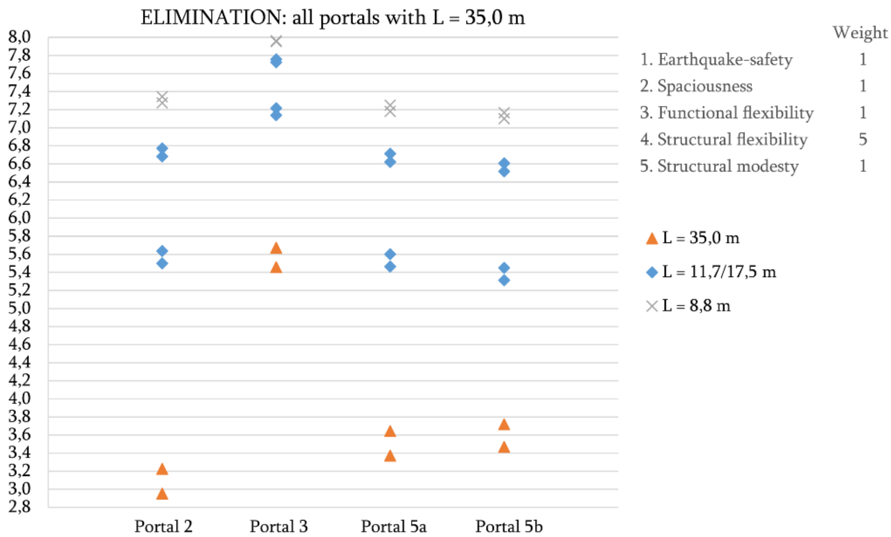

Figure 22 – Second round: third elimination (b)

*Number of models: **16***

Elimination of "Portal 5b"

As a last step in this elimination round, Portal 5a and 5b are compared to one another. Portal 5a has a slightly lower arch than 5b. The upside of this is that the length of the element is smaller for Portal 5a, but Portal 5b will score a bit better on Spaciousness due to the higher arch. Looking at Figure 23, in which all criteria have the same weight, it turns out Portal 5a gets a slightly higher score. The difference in spaciousness between the two portals is not big enough to weigh up against the smaller element size in Portal 5a. In conclusion, Portal 5b will be eliminated and only 12 models are left to look into.

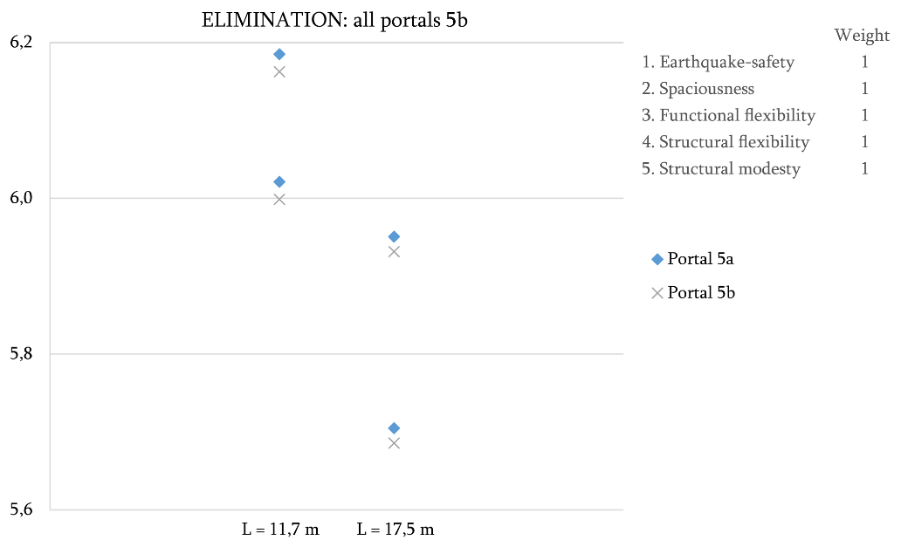

Figure 23 – Second round: fourth elimination

Number of models: 12

Summary

Only 12 models remain to be further looked into, four of Portal 2, four of Portal 3 and four of Portal 5a. To summarize, the following cuts have been made:

1. All portals with a core-to-core distance of 6,5 m and 7,1 m
2. "Portal 2" with a height of G = 8,0 m
3. All portals with a span of 8,8 m and 35,0 m
4. "Portal 5b"

3.1.3 Third elimination round

Overview

The following 12 models – all of which have a core-to-core distance of 4,3 m – are left to research:

Portal 2	G_{min} = 12,0 m	L_{min}	= 11,7 m
		L_{max}	= 17,5 m
	G_{max} = 16,0 m	L_{min}	= 11,7 m
		L_{max}	= 17,5 m
Portal 3	G_{min} = 8,0 m	L_{min}	= 11,7 m
		L_{max}	= 17,5 m
	G_{max} = 12,0 m	L_{min}	= 11,7 m
		L_{max}	= 17,5 m
Portal 5a	G_{min} = 8,0 m	L_{min}	= 11,7 m
		L_{max}	= 17,5 m
	G_{max} = 12,0 m	L_{min}	= 11,7 m
		L_{max}	= 17,5 m

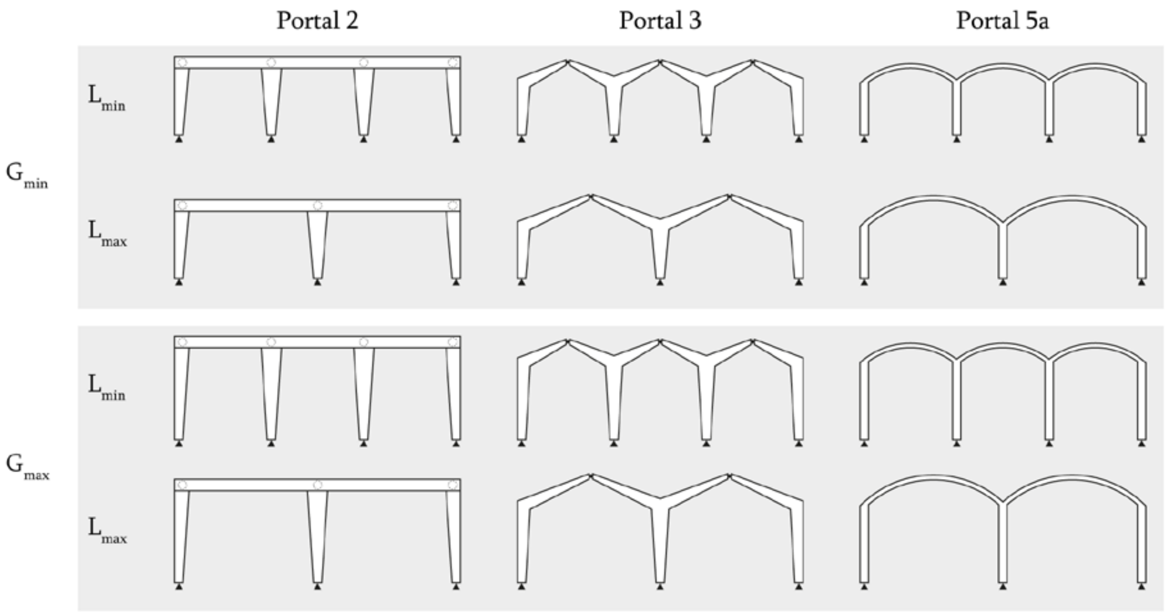

Figure 24 – Twelve remaining models

Final eliminations

Figure 25 shows the overall score of the 12 models that remain. The first thing to notice is that all models with a minimum span L_{min} = 11,7 m score better than the variants with a span of L_{max} = 17,5 m. The models with a minimum span L_{min} and a maximum column height G_{max} – in case of Portal 2 16,0 m, in case of Portal 3 and 5a 12,0 m – score best.

Portal 3 seems to be the clear winner, with three variants scoring highest out of all portals. However, to make the final elimination, all weighted aspects should be looked into a bit more closely.

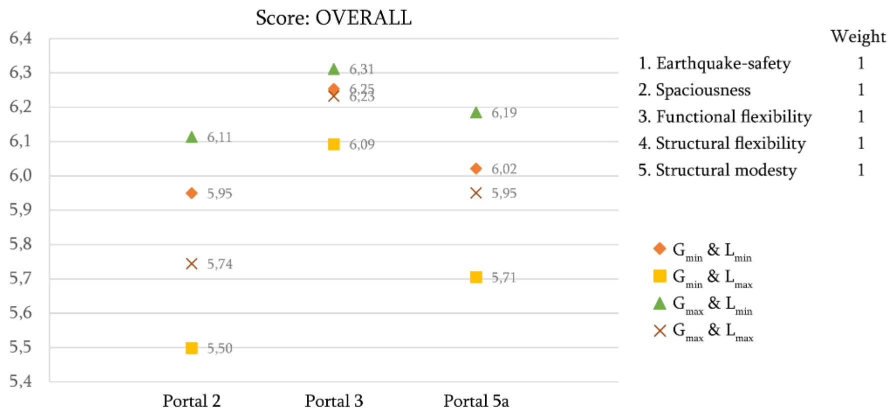

Figure 25 – Third round: overall score

In general, the overall score shows that Portal 2 is least beneficial. This is also reflected in the weighted scores, shown from Figure 26 to Figure 30: Portal 2 only scores a tad higher than the alternatives for Spaciousness (Figure 27), but lacks in the other departments.

Portal 3 is the winner in most of the cases, which would explain its high overall score. The cause of this peak is easily explained by looking at its score for Structural Flexibility (Figure 29), which is measured by the length of the beams. Portal 3 scores very high on this as the kinked roof consists of two elements instead of one, heavily decreasing the length of the beams. This difference causes Portal 3 to score high in the other weightings as well, as the structural flexibility is still taken into consideration, be it with a lower weight.

However, Portal 5 has a highly rated characteristic to it as well: it scores highest when it comes down to Structural Modesty (Figure 30), an aspect quantified by the height of the beams. The curved shape of the beams is very efficient in transferring loads, and thus the cross-sections of the elements can be quite small. It does not peak as high as Portal 3 in case of Structural Flexibility, but its benefits are worth keeping this model in the running.

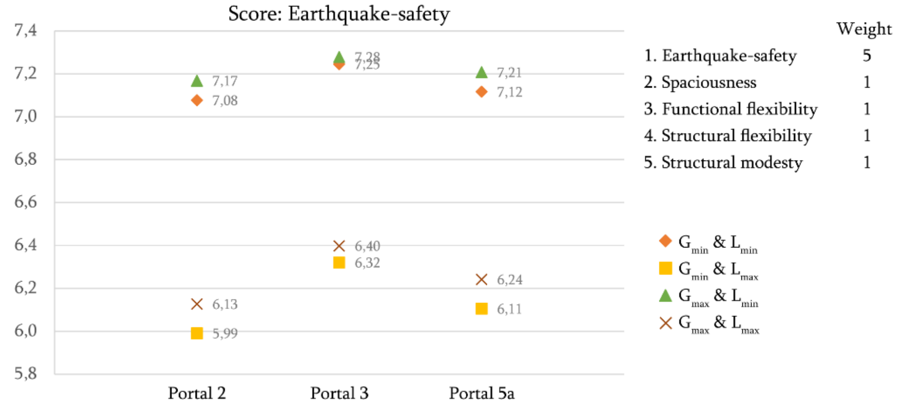

Figure 26 – Third round: score on earthquake-safety

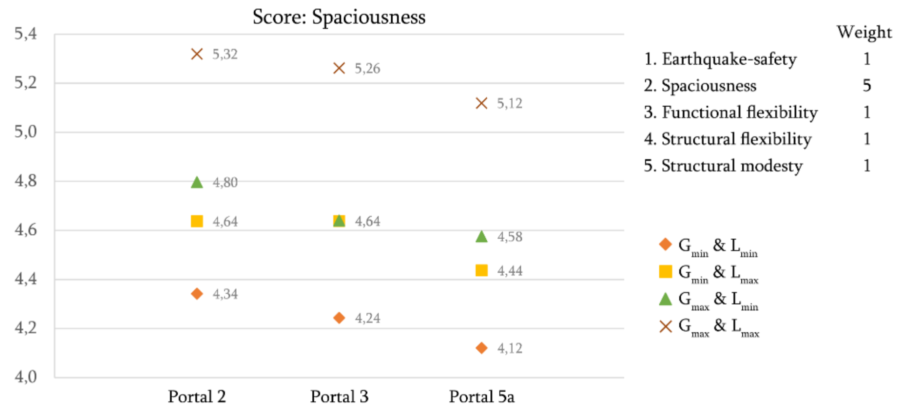

Figure 27 – Third round: score on spaciousness

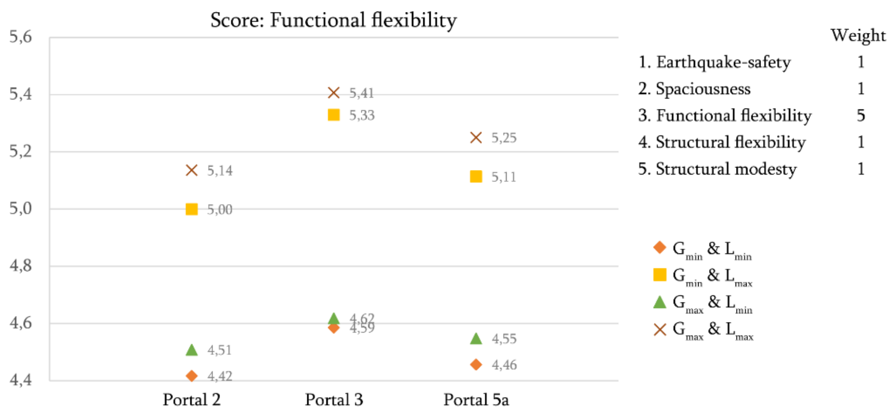

Figure 28 – Third round: score on functional flexibility

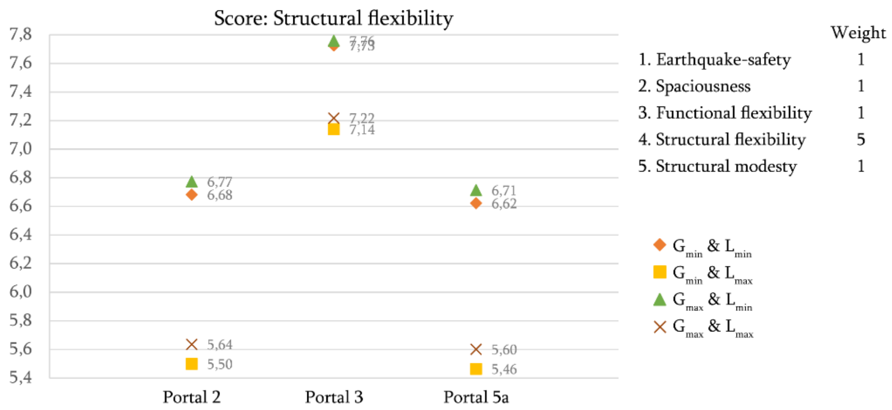

Figure 29 – Third round: score on structural flexibility

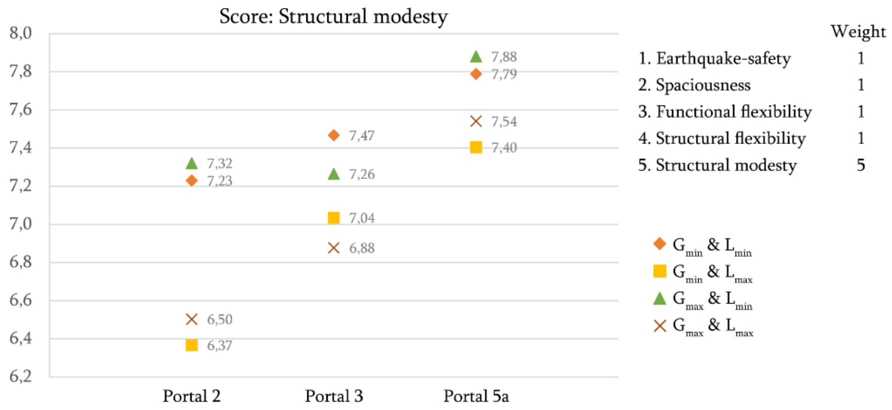

Figure 30 – Third round: score on structural modesty

In summary, Portal 2, all portals with L_{max} (a span of 17,5 m) and the left-over portals with G_{min} (a column height of 8,0 m in portal 3 and 5a) are eliminated in this final round. The winner is Portal 3 with G = 12,0 m and L = 11,7 m. But as it lacks mostly in one department (Structural Modesty), one other portal has made it to the finish line as well: Portal 5a with G = 12,0 m and L = 11,7 m.

Number of models: 2

3.2 Outcome

Figure 31 and Figure 32 shows a 3D-impression of the two outcomes on the Piazza del Duomo in L'Aquila. The structures are very similar, and both have their own set of advantages and disadvantages.

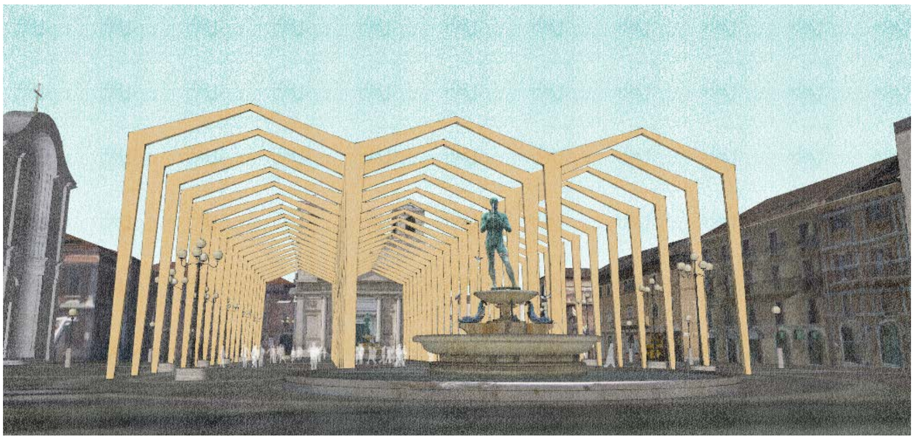

Figure 31 – Outcome 1: Portal 3 / G = 12,0 m / L = 11,7 m / c.t.c. = 4,3 m

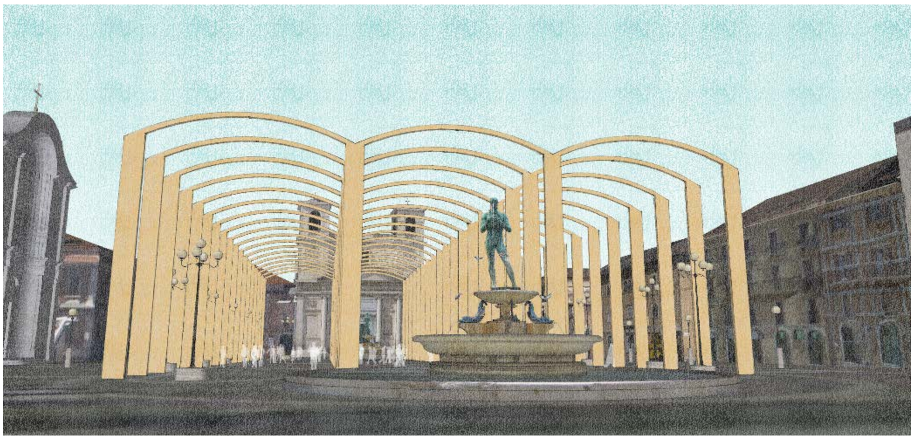

Figure 32 – Outcome 2: Portal 5a / G = 12,0 m / L = 11,7 m / c.t.c. = 4,3 m

4 Discussion

A quantitative design approach like the one set out in this research paper is an interesting and useful tool in the early stages of a design process. However, its drawbacks should not be overlooked. The outcome seems to be very black-and-white: the higher the grade, the better the construction. This is true up to a certain degree. However, it should be realised, the grading limits have been assigned by the researcher and are therefore flexible. This means that though within each specific criterion all portals can be compared fairly, comparing the criterions with one another is a bit more difficult: a 6 in one department is not necessarily better than a 5 in another. In case of this specific research it would mean that Portal 5a could have easily come out a clear winner over Portal 3, had the boundaries for grading been a bit different. This is why Portal 5a has been declared one of the outcomes too, though its overall weighted grade was lower. Therefore, as has been done in this research paper, it is of the utmost importance to handle the results carefully in a quantitative research-by-design method, bearing these limitations in mind.

For the sake of this quantitative research, a lot of the characteristics have been simplified. Though this should not be a problem during the initial stage of the design process, it is very important to keep this in mind in further design developments. The most important ones are (1) the simplification of the earthquake-safety of the structure to merely its structural scale; and (2) the simplification of the 3D-experience of the space to the basic numerator "Spaciousness", expressed by the maximum uninterrupted volume underneath the structure.

The earthquake-safety of a structure entails many aspects of its design: the structural scale, the materials, the full building shape, the joint designs, the finishing, the foundation and even the ground it is build on, just to name a few. For this research paper, a simplification has been made by expressing the criterion "Earthquake-safety" merely by the roof surface that would be expected to fail in case of the collapse of one structural element. Though this might be justified during this early-on stage, as no detailed design decisions have yet been made, it is important to keep in mind only one aspect of the actual earthquake-safety has been reviewed. In the following phases, especially during the definite dimensioning and detailing of the structure, the earthquake-safety should be reviewed in all its aspects.

The spaciousness has been expressed by the maximum free and uninterrupted volume underneath the structures. This means there is a direct connection between the height of the structure and its grading with respect to spaciousness, and in none of the criteria had the height of the structure a negative influence. However, big heights could have downsides in the actual situation. For instance, the supporting structure could have quite large dimensions, and a big height could even be considered unpleasant as the feeling of shelter dissipates. These are factors that can not easily be quantified, but they should definitely be taken into account in the following design steps. It is therefore recommended not to stick too tightly to the height of the model outcomes, but to take this as a lead and to try out different variations in a qualitative review.

The height of the final outcomes is not the only design aspect that should not be taken too strictly. The goal of this research was not to come to a final design, but rather to provide insight in different aspects and a framework for the following design process. It is a first step and many more can follow. An example: it is recommended there should be three spans over the width of the Piazza del Duomo. One could imagine, however, that not all these three spans are the same size nor the same height. These are aspects that should be further investigated during the design process.

5 Conclusion

Figure 33 – Final outcomes

During this research paper, 168 models have been investigated according to simplified assessment criteria: earthquake-safety, spaciousness, functional flexibility, structural flexibility and structural modesty.

Through step-by-step elimination, this group of models has been narrowed down to only two. Both models have spans of 11,7 m and a column height of 12,0 m. The difference between the two is a kinked beam shape (Portal 3) and a curved one (Portal 5a).

Portal 3 scores very high due to the fact its structural elements are relatively short as the kinked roof beam consists of two elements instead of one, but it scores relatively low when it comes down to the height of its structural elements.

Portal 5a, however, gets high grades on structural modesty as its beams are very small due to its efficient curved shape, but the length of the structural elements is a lot bigger than those of Portal 3.

In the ideal design the advantages from both would be integrated. It could prove and interesting design task to design a curved structure (the advantage of Portal 5a) with relatively short and straight structural elements (the advantage of Portal 3). This should happen with all aforementioned and other (qualitative) aspects kept in mind in their broadest sense, not just their simplified version.

Most of all, it needs be kept in mind that the outcome of this paper is a tool, a framework for further design. It is by no means a definite design itself, but it provides a good first step.

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APPENDIX: SCORES

In this Appendix the scores are presented for all weightings and relevant models. The lowest three scores out of all are marked orange, while the best three are marked green. The scores for the remaining twelve models in the last elimination round (see paragraph 3.1.3) are typed in red.

Score: OVERALL

	Weight
1. Earthquake-safety	1
2. Spaciousness	1
3. Functional flexibility	1
4. Structural flexibility	1
5. Structural modesty	1

Portal 2		c.t.c. 4,3	c.t.c. 6,5	c.t.c. 7,1
G = 8,0 m	L = 8,8 m	6,05	5,66	5,55
	L = 11,7 m	5,79	5,27	5,11
	L = 17,5 m	5,25	4,47	4,24
	L = 35,0 m	4,02	3,62	3,56
G = 12,0 m	L = 8,8 m	6,18	5,79	5,67
	L = 11,7 m	5,95	5,43	5,28
	L = 17,5 m	5,50	4,72	4,49
	L = 35,0 m	4,51	4,11	4,05
G = 16,0 m	L = 8,8 m	6,30	5,91	5,79
	L = 11,7 m	6,11	5,59	5,44
	L = 17,5 m	5,74	4,96	4,73
	L = 35,0 m	5,00	4,60	4,54
Portal 3		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	6,32	5,95	5,88
	L = 11,7 m	6,25	5,78	5,68
	L = 17,5 m	6,09	5,40	5,25
	L = 35,0 m	5,75	5,56	5,56
G = 12,0 m	L = 8,8 m	6,33	5,95	5,88
	L = 11,7 m	6,31	5,82	5,72
	L = 17,5 m	6,23	5,52	5,37
	L = 35,0 m	6,13	5,93	5,93
Portal 5a		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	6,14	5,85	5,77
	L = 11,7 m	6,02	5,64	5,53
	L = 17,5 m	5,71	5,08	4,92
	L = 35,0 m	5,27	5,17	5,17
G = 12,0 m	L = 8,8 m	6,26	5,98	5,90
	L = 11,7 m	6,19	5,80	5,69
	L = 17,5 m	5,95	5,32	5,16
	L = 35,0 m	5,76	5,66	5,66
Portal 5b		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	6,12	5,83	5,75
	L = 11,7 m	6,00	5,61	5,51
	L = 17,5 m	5,69	5,06	4,90
	L = 35,0 m	5,44	5,34	5,34
G = 12,0 m	L = 8,8 m	6,24	5,95	5,88
	L = 11,7 m	6,16	5,78	5,67
	L = 17,5 m	5,93	5,30	5,15
	L = 35,0 m	5,89	5,79	5,79

Score: Earthquake-safety

	Weight
1. Earthquake-safety	5
2. Spaciousness	1
3. Functional flexibility	1
4. Structural flexibility	1
5. Structural modesty	1

Portal 2		c.t.c. 4,3	c.t.c. 6,5	c.t.c. 7,1
G = 8,0 m	L = 8,8 m	7,55	6,69	6,46
	L = 11,7 m	6,99	5,84	5,52
	L = 17,5 m	5,85	4,14	3,66
	L = 35,0 m	2,68	2,45	2,42
G = 12,0 m	L = 8,8 m	7,62	6,76	6,52
	L = 11,7 m	7,08	5,93	5,61
	L = 17,5 m	5,99	4,27	3,80
	L = 35,0 m	2,95	2,73	2,69
G = 16,0 m	L = 8,8 m	7,69	6,83	6,59
	L = 11,7 m	7,17	6,02	5,70
	L = 17,5 m	6,13	4,41	3,93
	L = 35,0 m	3,22	3,00	2,97
Portal 3		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	7,70	6,86	6,64
	L = 11,7 m	7,25	6,13	5,84
	L = 17,5 m	6,32	4,65	4,22
	L = 35,0 m	3,64	3,53	3,53
G = 12,0 m	L = 8,8 m	7,71	6,86	6,64
	L = 11,7 m	7,28	6,15	5,86
	L = 17,5 m	6,40	4,72	4,28
	L = 35,0 m	3,85	3,74	3,74
Portal 5a		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	7,60	6,80	6,58
	L = 11,7 m	7,12	6,05	5,76
	L = 17,5 m	6,11	4,47	4,04
	L = 35,0 m	3,37	3,31	3,31
G = 12,0 m	L = 8,8 m	7,67	6,87	6,65
	L = 11,7 m	7,21	6,14	5,85
	L = 17,5 m	6,24	4,61	4,17
	L = 35,0 m	3,64	3,59	3,59
Portal 5b		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	7,59	6,79	6,57
	L = 11,7 m	7,10	6,03	5,74
	L = 17,5 m	6,09	4,46	4,02
	L = 35,0 m	3,47	3,41	3,41
G = 12,0 m	L = 8,8 m	7,66	6,86	6,64
	L = 11,7 m	7,20	6,13	5,83
	L = 17,5 m	6,23	4,60	4,16
	L = 35,0 m	3,72	3,66	3,66

Score: Spaciousness

	Weight
1. Earthquake-safety	1
2. Spaciousness	5
3. Functional flexibility	1
4. Structural flexibility	1
5. Structural modesty	1

Portal 2		c.t.c. 4,3	c.t.c. 6,5	c.t.c. 7,1
G = 8,0 m	L = 8,8 m	3,85	3,64	3,57
	L = 11,7 m	3,89	3,60	3,51
	L = 17,5 m	3,95	3,52	3,39
	L = 35,0 m	4,36	4,14	4,11
G = 12,0 m	L = 8,8 m	4,19	3,98	3,91
	L = 11,7 m	4,34	4,05	3,97
	L = 17,5 m	4,64	4,20	4,08
	L = 35,0 m	5,73	5,50	5,47
G = 16,0 m	L = 8,8 m	4,54	4,32	4,25
	L = 11,7 m	4,80	4,51	4,42
	L = 17,5 m	5,32	4,89	4,76
	L = 35,0 m	7,09	6,87	6,84
Portal 3		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	4,05	3,85	3,81
	L = 11,7 m	4,24	3,98	3,92
	L = 17,5 m	4,64	4,26	4,17
	L = 35,0 m	6,19	6,09	6,09
G = 12,0 m	L = 8,8 m	4,34	4,13	4,08
	L = 11,7 m	4,64	4,37	4,31
	L = 17,5 m	5,26	4,87	4,78
	L = 35,0 m	7,50	7,38	7,38
Portal 5a		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	3,96	3,80	3,76
	L = 11,7 m	4,12	3,91	3,85
	L = 17,5 m	4,44	4,09	4,00
	L = 35,0 m	5,98	5,92	5,92
G = 12,0 m	L = 8,8 m	4,30	4,14	4,10
	L = 11,7 m	4,58	4,36	4,30
	L = 17,5 m	5,12	4,77	4,68
	L = 35,0 m	7,34	7,29	7,29
Portal 5b		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	3,97	3,81	3,77
	L = 11,7 m	4,15	3,94	3,88
	L = 17,5 m	4,52	4,17	4,09
	L = 35,0 m	6,47	6,41	6,41
G = 12,0 m	L = 8,8 m	4,31	4,15	4,11
	L = 11,7 m	4,61	4,39	4,33
	L = 17,5 m	5,21	4,86	4,77
	L = 35,0 m	7,72	7,66	7,66

Score: Functional flexibility

	Weight
1. Earthquake-safety	1
2. Spaciousness	1
3. Functional flexibility	5
4. Structural flexibility	1
5. Structural modesty	1

Portal 2		c.t.c. 4,3	c.t.c. 6,5	c.t.c. 7,1
G = 8,0 m	L = 8,8 m	4,06	3,84	3,78
	L = 11,7 m	4,33	4,04	3,95
	L = 17,5 m	4,86	4,43	4,30
	L = 35,0 m	6,68	6,45	6,42
G = 12,0 m	L = 8,8 m	4,13	3,91	3,84
	L = 11,7 m	4,42	4,13	4,04
	L = 17,5 m	5,00	4,57	4,44
	L = 35,0 m	6,95	6,73	6,69
G = 16,0 m	L = 8,8 m	4,19	3,98	3,91
	L = 11,7 m	4,51	4,22	4,13
	L = 17,5 m	5,14	4,70	4,57
	L = 35,0 m	7,22	7,00	6,97
Portal 3		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	4,20	4,00	3,96
	L = 11,7 m	4,59	4,32	4,27
	L = 17,5 m	5,33	4,95	4,86
	L = 35,0 m	7,64	7,53	7,53
G = 12,0 m	L = 8,8 m	4,21	4,00	3,96
	L = 11,7 m	4,62	4,35	4,29
	L = 17,5 m	5,41	5,01	4,93
	L = 35,0 m	7,85	7,74	7,74
Portal 5a		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	4,11	3,95	3,90
	L = 11,7 m	4,46	4,24	4,18
	L = 17,5 m	5,11	4,76	4,68
	L = 35,0 m	7,37	7,31	7,31
G = 12,0 m	L = 8,8 m	4,17	4,01	3,97
	L = 11,7 m	4,55	4,33	4,28
	L = 17,5 m	5,25	4,90	4,81
	L = 35,0 m	7,64	7,59	7,59
Portal 5b		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	4,09	3,93	3,89
	L = 11,7 m	4,44	4,23	4,17
	L = 17,5 m	5,10	4,75	4,67
	L = 35,0 m	7,47	7,41	7,41
G = 12,0 m	L = 8,8 m	4,16	4,00	3,96
	L = 11,7 m	4,54	4,32	4,26
	L = 17,5 m	5,24	4,89	4,80
	L = 35,0 m	7,72	7,66	7,66

Score: Structural flexibility

	Weight
1. Earthquake-safety	1
2. Spaciousness	1
3. Functional flexibility	1
4. Structural flexibility	5
5. Structural modesty	1

Portal 2		c.t.c. 4,3	c.t.c. 6,5	c.t.c. 7,1
G = 8,0 m	L = 8,8 m	7,21	6,99	6,93
	L = 11,7 m	6,59	6,30	6,22
	L = 17,5 m	5,36	4,93	4,80
	L = 35,0 m	2,68	2,45	2,42
G = 12,0 m	L = 8,8 m	7,28	7,06	6,99
	L = 11,7 m	6,68	6,39	6,31
	L = 17,5 m	5,50	5,07	4,94
	L = 35,0 m	2,95	2,73	2,69
G = 16,0 m	L = 8,8 m	7,34	7,13	7,06
	L = 11,7 m	6,77	6,48	6,40
	L = 17,5 m	5,64	5,20	5,07
	L = 35,0 m	3,22	3,00	2,97
Portal 3		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	7,95	7,75	7,71
	L = 11,7 m	7,73	7,46	7,40
	L = 17,5 m	7,14	6,76	6,67
	L = 35,0 m	5,46	5,35	5,35
G = 12,0 m	L = 8,8 m	7,96	7,75	7,71
	L = 11,7 m	7,76	7,49	7,43
	L = 17,5 m	7,22	6,82	6,74
	L = 35,0 m	5,67	5,56	5,56
Portal 5a		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	7,18	7,02	6,98
	L = 11,7 m	6,62	6,41	6,35
	L = 17,5 m	5,46	5,11	5,03
	L = 35,0 m	3,37	3,31	3,31
G = 12,0 m	L = 8,8 m	7,25	7,09	7,05
	L = 11,7 m	6,71	6,50	6,44
	L = 17,5 m	5,60	5,25	5,16
	L = 35,0 m	3,64	3,59	3,59
Portal 5b		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	7,10	6,94	6,90
	L = 11,7 m	6,52	6,30	6,24
	L = 17,5 m	5,31	4,96	4,88
	L = 35,0 m	3,47	3,41	3,41
G = 12,0 m	L = 8,8 m	7,17	7,01	6,96
	L = 11,7 m	6,61	6,39	6,34
	L = 17,5 m	5,45	5,10	5,01
	L = 35,0 m	3,72	3,66	3,66

Score: Structural modesty

	Weight
1. Earthquake-safety	1
2. Spaciousness	1
3. Functional flexibility	1
4. Structural flexibility	1
5. Structural modesty	5

Portal 2		c.t.c. 4,3	c.t.c. 6,5	c.t.c. 7,1
G = 8,0 m	L = 8,8 m	7,59	7,15	7,01
	L = 11,7 m	7,14	6,55	6,36
	L = 17,5 m	6,23	5,35	5,06
	L = 35,0 m	3,71	2,58	2,42
G = 12,0 m	L = 8,8 m	7,66	7,22	7,08
	L = 11,7 m	7,23	6,64	6,45
	L = 17,5 m	6,37	5,48	5,19
	L = 35,0 m	3,98	2,86	2,69
G = 16,0 m	L = 8,8 m	7,73	7,29	7,14
	L = 11,7 m	7,32	6,73	6,54
	L = 17,5 m	6,50	5,62	5,33
	L = 35,0 m	4,25	3,13	2,97
Portal 3		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	7,67	7,31	7,27
	L = 11,7 m	7,47	7,01	6,95
	L = 17,5 m	7,04	6,40	6,31
	L = 35,0 m	5,81	5,29	5,29
G = 12,0 m	L = 8,8 m	7,45	7,03	6,99
	L = 11,7 m	7,26	6,76	6,70
	L = 17,5 m	6,88	6,20	6,11
	L = 35,0 m	5,79	5,22	5,22
Portal 5a		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	7,86	7,70	7,65
	L = 11,7 m	7,79	7,58	7,52
	L = 17,5 m	7,40	6,94	6,85
	L = 35,0 m	6,25	5,96	5,96
G = 12,0 m	L = 8,8 m	7,92	7,76	7,72
	L = 11,7 m	7,88	7,67	7,61
	L = 17,5 m	7,54	7,08	6,99
	L = 35,0 m	6,52	6,23	6,23
Portal 5b		**c.t.c. 4,3**	**c.t.c. 6,5**	**c.t.c. 7,1**
G = 8,0 m	L = 8,8 m	7,84	7,68	7,64
	L = 11,7 m	7,78	7,56	7,50
	L = 17,5 m	7,39	6,93	6,84
	L = 35,0 m	6,34	6,06	6,06
G = 12,0 m	L = 8,8 m	7,91	7,75	7,71
	L = 11,7 m	7,87	7,65	7,60
	L = 17,5 m	7,53	7,07	6,98
	L = 35,0 m	6,59	6,31	6,31