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A matter of speed: The impact of material choice in post-disaster reconstruction

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Abstract: The effects of urbanization and climate change are dangerously converging. The most affected populations are the urban poor, settled in informal settlements vulnerable to increasingly frequent disasters. This severely contributes to the existing housing gap of these regions, already struggling with housing demand. The speed of shelter delivery becomes key for an efficient response in order to prevent spontaneous informal resettlements on unsafe lands. The present study aims to understand the impact of material choice on post-disaster shelters delivery through a multiscale analysis of construction speed. The scales considered are: Constructive technology, Shelter Unit and Post-disaster settlement. At the the Constructive technology scale, nine different reconstruction solutions for the Nepal earthquake are compared, covering a range from local to industrialized. Successively, twelve shelter designs by the International Federation of the Red Cross have been studied under the same lens at the Shelter unit scale and for Post-disaster settlements. The study identifies a clear correlation between material procurement and speed at the constructive technology scale. At the shelter scale, this correlation becomes secondary and construction time is seriously impacted by the complexity of roof design. Moving to the settlement scale, the choice of local over industrialized materials seems to drive the speed again. The study indicates how a multiscale approach is necessary to analyze the impacts of material selection, providing efficient guidelines for post-disaster reconstruction. Beyond that, it highlights that effective reconstruction can be developed with diverse materials, but its emergency responsiveness can seriously be compromised by a non-appropriate design.

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A MATTER OF SPEED: THE IMPACT OF MATERIAL CHOICE IN POST-DISASTER RECONSTRUCTION

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Keywords: post-disaster, reconstruction, shelters, material selection, large scale

1. Introduction

Since 2009, an estimated one person per second has been displaced by a natural disaster worldwide [1]. Ongoing urbanization, combined with the escalating consequences of climate change [2,3], is leading to an increase in the impact of disasters on the world's built environment [4].

Currently, eighty percent of cities, home to 1.9 billion people, are located in areas that are highly exposed to the occurrence of natural disasters. Cities in the less developed regions face a higher threat of hazards and are more vulnerable to disaster-related losses than those in more developed regions [5]. Moreover, climate change is expected to increase the intensity of certain natural hazards, and it is projected that low-income countries will be the most severely affected by them [2]. The impact of disasters on the built environment is, in fact, particularly high in developing countries, estimated at 20 times more than in developed countries [6] because of the often widespread weak construction and consequently extensive devastation, leaving many in need of a shelter in countries already struggling with their everyday economy and housing gap. Hence, in post-disaster recovery programs, high priority and resources are allocated to housing and infrastructure reconstruction [7,8]. Thus, the issue of how to cope with effective delivery in large-scale post-disaster reconstruction projects has become a key challenge. The current paper specifically targets the topic of speed in the reconstruction process.

Post-disaster reconstruction confronts the diverging time constraints of a displaced population in need for shelters, as left homeless from the catastrophe, together with the requirement of agencies planning programs aiming not only to provide a short term solution, but a resilient long term response. This longer term prevision is intended not only to accommodate a socio-economic restauration, but possibly and improvement if compared to pre-disaster conditions, as recommended in by the Sendai agreement and the globally adopted Building Back Better reconstruction guidelines [9–11]. In the meantime, the spontaneous tendency of the population is to rush into restoring livelihood "back to normal", often ending up in replicating previous vulnerability by building in disaster prone areas or adopting unsafe means of construction [12,13]. This circumstance consequently puts pressure on the authorities and agencies in delivering a response [14,15], that could indeed meet the speed required, while though fail on socio-economic aspects as in the case of the donor-driven reconstruction for the 2004 post-tsunami reconstruction in Indonesia [16]. From these studies it is possible to extract the importance of providing a quick recovery in order to avoid the establishment of unsafe building structures, socially inadequate housing solutions or self-resettling of communities in disaster prone areas. Nevertheless, it is key to consider that speed of recovery is not the only driver of a reconstruction program, and can damage the success of the program if leading to non-appropriate building solutions compromising structural integrity or social and economic adequateness of the project [16]. The post-tsunami resident satisfaction study carried out in Aceh for example revealed that the speed of being promised is a house is actually a more prominent driver than the effective speed of delivery of the house [17].

Post-disaster reconstruction projects are faced with obstacles going beyond the regular construction issues and are prone to deliver inadequate building solutions [18]. This can be directly related to the need for rapid reaction under challenging conditions. Even though these circumstances are well known, the necessary strategies to overcome these difficulties seem to be less clear [18]. The main bottlenecks in reconstruction projects have been clearly identified: (i) supply chain dysfunction, (ii) resources shortage, (iii) corruption, (iv) lack of coordination among agencies, (v) poor construction skills and (vi) infrastructure breakdown. Solutions to reduce these obstacles are still under discussion [9,19–22]. Specifically, Bilau [23] classified seven main management issues arising in large-scale housing reconstruction programs: (i) human resource issues, (ii) workmanship and quality management issues, (iii) monitoring and control issues, (iv) coordination and communication issues, (v) logistics and supplies, (vi) health and safety issues, and (vii) financial management [23]. Construction materials can be related to more than one of the listed bottlenecks.. As a consequence of the hazard, the majority of local production facilities and supply systems in manufacturing industries are likely to be damaged, leading the construction market into disorder [24]. This leads to price increase for up to 130% for instance in the post-Wenchuan earthquake reconstruction in China [10]. After the 2004 Indian Ocean tsunami, a lack of building materials such as sand, stone, cement, timber and brick in Indonesia created a major bottleneck for housing recovery [24,25]. As Jayasuriya observed in Sri Lanka [26], the impact of the tsunami intensified pre-existing shortages, fuelled inflation, constrained the government capacity, and affected housing reconstruction. Numerous International Organizations, such as IFRC and UN agencies, also highlighted the importance of resource availability as the key element to optimize recovery efforts [19,27–30].

But the strategies under discussion are mainly intended for policy makers and not so much for construction engineers and designers. This technical approach can be seen at different levels: material, building and settlement. In the following sections, a detailed literature review will show the state of the discussion at these three fundamental scales.

1.1. Scale 1: Constructive Technology

Every post-disaster reconstruction project is faced with the challenge of quickly responding to the crisis at hand using available resources, resulting in either a global or local material choice[1]. Material selection, polarized in these two categories of Local vs. Global, carries consequences extending past the field of materials science.

Local materials such as bamboo, earth, or stone have been identified by many as the most effective choice for post-disaster reconstruction. Used in vernacular construction techniques, they are in fact strictly related to their territory and culture and thus must not only be available in the direct aftermath of a disaster but also be climatically appropriate [10]. In fact, this architectural style takes care of climatic and energy conserving features providing enhanced thermal comfort. Moreover, their adoption often results from them being economically valuable and socially accepted by low-income communities. On the specific topic of social acceptance of building materials, extensive research has been carried out by Duyne Barenstein in Gujarat through a post-disaster evaluation of diverse post-disaster programs. [32,33]. The study shows that satisfaction of beneficiaries that received dwellings built in local materials (in the case observed, through a self-driven approach) was optimal (100%), much higher than the one of beneficiaries of a contractor-led development employing industrialized materials as hollowed concrete blocks (31%). Nevertheless, it is to be observed that many factors contribute to such an evaluation, as the second group of beneficiaries also questioned the quality of the construction expressing only a 36% satisfaction. The same study also provides reflection on how "seismic safety can be achieved without the introduction of exogenous building materials and techniques and is not incompatible with traditional building styles".

Dikmen et al. in Turkey also contributes to the discourse [34], through an anthropological approach, proving the strong link between shelter design and materials and reconstruction project success on a long term. Furthermore, the availability of building materials in the territory allows for local labor adoption, maintaining the use of traditional techniques and facilitating maintenance in the future due to the availability of materials and skills [35,36]. On a different note, it is to be mentioned that local materials are not always preferred by beneficiaries. As expressed by Rashid and Ara in their overview on the influence of vernacular architecture on Asian modernism, "one tends to suppose that vernacular architecture is a kind of architecture, in opposition to the modern one, lacking of technological efficiency". [37] The study from Giesekam et al. [38] on the adoption of low carbon technology adds to this the important discourse on the disconnection of perception and experience, showing that perceptions, even if not backed by direct experience, actually obstacles the possible selection of alternative materials. These tendencies can lead to the rejection of local technologies as they might associated with poor construction methods, where poor refers both to the lack of performance and to the belonging of a certain social class, especially true in the periurban areas.

It is though not to be forgotten that the success of a project comes from the appropriateness of diverse factors, of which material is only one, as design, typology, building process, skills and many more [39].From a social perspective, the utilization of industrialized –Global- technologies, able to achieve higher structural performance, instead often embeds the idea of shelter as a product rather than an inclusive process [40]. If it is true that the adoption of industrialized technologies might find resistance in terms of social adoption, it is also to be said that, through a proper transition to the new technologies, high levels of satisfaction can be reached. This is the case for the post-earthquake reconstruction in Pakistan (2005), where, through adequate training and adaptation from unreinforced stone masonry towards slightly more industrialized technologies, successful results were achieved, as seen in the work from van Leersum and Arora [41].
Beyond that, it is important to remember that the adoption of industrialized solutions can lead to very different results, ranging from optimized projects [42] to more resource-consuming results from an environmental and economic perspective [31].

The position of UNHCR on material procurement clearly shows the complexity of the issue, strictly related to the contingent case. According to the emergency Handbook, local procurement is to be favored for its lower price, lower transport cost, speed and flexible delivery, together with social acceptance. Disadvantages for the local purchase are also highlighted, such as the possibility of higher prices, poor quality, and inability to meet specifications and to supply the volume of goods demanded [43].

At this scale, the discussion that the debate gravitates to regarding material selection is in fact mainly focused on the socio-cultural consequences of its implementation rather than capacity to boost the construction. The issue of speed, in fact, seems not to be considered a relevant point of this discussion.

1.2. Scale 2: Shelter Unit

At the scale of the shelter unit, material choice questions are replaced by those of different manufacturing/constructive strategies. These strategies can be grouped into two main categories: in situ or prefabricated construction. Both approaches, adopted and implemented in many projects world-wide and, have proven to be viable. The first is mainly used in combination with local materials, embedding direct involvement of community members in both design and construction phases, leading to a higher sense of ownership and community involvement [10]. The latter, aiming to achieve large-scale production of easy-to-assemble building solutions, derives from decades of research conducted by industries and aims to reduce the building time to assembly time while overcoming the incapacity of the local production system to cope with the emergency, shifting the production to areas untouched by the disaster.

The key issue with prefabrication is often identified as cultural acceptability and the limited potential to adapt the basic structure in the future. Many of these systems had been developed for housing markets in non-seismic countries and are not suitable for the implementation case [35]. It is, in fact, recognized that, “behind the quantitative aspects of reconstruction lie complex social and cultural requirements, implicit at both at the community and the family levels” [18] on which prefabricated solutions provide no added value. The backdrop of prefabricated systems does not uniquely rely on its social impact: they require a transportation phase that often incurs a significant increase in the construction economic and environmental burden. The example of the fast-to-assemble housing prototype developed in the late nineties by the Auroville Earth Institute synthesizes the economic issue, requiring a transportation cost alone equal to the cost of manufacturing [44]. Concerning the environmental performance of prefabricated post-disaster shelters, the work of Atmaca [45] can provide understanding of the life-cycle energy consumption due to the construction phase and the operational one, but it allows for no comparison with shelters developed with local resources.

Prefabricated design is rooted in modernist studies on mechanization, fast deployment and the possibility of reassembling elsewhere, extensively discussed by Le Corbusier and celebrated in the prototypical pioneering work of Buckminster Fuller (Dymaxion House 1927) and Jean Prouve (Papillon 6x6 Demountable House 1944). Many other architects have explored this field and left a remarkable legacy, as for the case of the utopic approach presented by Archigram in “Plug-in City” or the notable intervention of the Israeli-Canadian architect Moshe Safdie for the world exposition Habitat in Montreal [46–49]. The above-cited works are still objects of study all over the world and have contributed significantly to the development of prefabrication in the last decades from a design perspective. Despite these multiple examples of prototypical successful practices, consolidated in the 80s and 90s in the manufacturing sector and coming back to the news currently with the most recent IKEA design for rapid shelter deployment, many have been arguing against the adoption of prefabricated solutions. In 1982, the United Nations Disaster Relief Organization made a clear statement on the topic, recommending avoidance of “designing, manufacturing and stockpiling prefabricated emergency shelter units (other than tents), as this solution is too costly and a waste of resources for developing countries” [50]. The International Federation of the Red Cross (henceforth referred to as IFRC), the only international organization having the topic of shelter in its mandate, recently officially backed the adoption of more local solutions, still without rejecting prefabrication-based designs for some reconstruction programs (as seen in Haiti, 2008).

30 years after the beginning of this debate, it is possible to say that a common agreement on the efficiency of prefabrication is still under discussion. Even if the development of prefabricated options relies on the need for quick construction processes, the current discussion gravitating around its

adoption, in contrast with in situ technologies, is focused on its societal consequences. Social inclusion and acceptance, environmental footprint and economic cost are investigated in relationship to the advantages of prefabrication, while no main effort is invested in the implementation of the construction speed itself. At this scale again, it is then possible to say that, despite the acknowledged relevance of construction speed, the discussion is instead shifted to other aspects of the process.

1.3. Scale 3: Post-disaster settlement

At the settlement scale, the question of resource requirement and supply becomes a key question [51]. Models have been developed to support the planning phase by assessing total resources (investment and materials) of the economy required to meet housing need [52]. The extensive study carried out by ARUP [35] after the Aceh reconstruction explores well the difficulty of construction management for large scale post-disaster programs and its influence on the effectiveness of the response.

Despite consistent research on the topic, mainly addressing logistic issues over design and engineering ones, there is no agreement on how material choice affects the large-scale construction in terms of speed of delivery.

The review of this scale highlights the multifaceted characteristics of resource procurement. Extensive studies on supply chain management in the humanitarian sector have been carried out, addressing the issue of speed from a logistic perspective [53–55]. Despite the relevance of these studies, it is important to recognize that none of the recommendations proposed are related to the design choices, which doesn’t enable architects and engineers to propose the appropriate reconstructive solution

1.4. Multiscale approaches

Multiscale methods have been explored in various fields related to disaster recovery, proving their validity. Due to the multifaceted characteristics of the emergency, their fields of application have ranged broadly: from urban disaster mitigation planning [56] to socio-ecological studies on community resiliency [57] and disaster preparedness [58]. More specifically on post-disaster reconstruction strategies, the work of Maly shows how the issue of scales is a key challenge for project delivery [59]. This paper specifically focuses on “people centered housing recovery” as a framework with multiple aspects (policy, process, and housing form) applied to multiple scales (disaster area, community, and individual household), and highlights a critical need to bridge the gap between a demonstration pilot project and an approach to reconstruction reaching the large scale.

These projects have shown the effectiveness of multiscale methods in understanding the complex dynamics and consequences of a small-scale issue on a higher scale, serving as support for policy makers.

The present study aims therefore to develop a multiscale assessment methodology to highlight the different drivers influencing the speed of delivery in reconstruction projects, aiming to support designers and construction managers from a technical perspective, in order to increase the effectiveness of their reconstruction projects. To do so, an assessment of post-disaster shelter delivery will be carried out, focusing on the three identified scales: (i) constructive technology, (ii) shelter unit and (iii) settlement. The assessment will be conducted on different case studies according to data availability.

2. Data and methods

Three different scales have been identified for the study: Constructive Technology, Shelter Unit and Post-Disaster Settlement.

These scales were selected for their relevance in a post-disaster reconstruction context, since they allow for an understanding of the impact of material choice on the economic and time cost of the project according to different decision makers involved in the reconstruction projects (engineers and material scientists, architects and logistics).

For the three different scales of the analysis, constructive technologies were assessed regarding their building time and cost related to their material procurement. In more detail, this has been identified by the terms *local* and *imported* for their literal translations related to the procurement.
The ratios of imported materials of different constructive technologies have been analyzed in correlation with the construction speed and economic cost at the three scales of constructive technology (referring to one square meter of wall build), shelter unit (referring to a complete shelter) and post-disaster reconstruction camp (considering the complete camp development).

2.1. Scale 1: Construction Technology

The assessment of different construction technologies at this scale was conducted according to different options suitable for the Thame Valley post-earthquake reconstruction in Nepal (2015). This specific context represents a relevant case study due to the isolated location of the reconstruction, situated in the Northeast of the country and accessible only by foot via a two-day hike from the closest city served by proper road access, i.e., Lukla. This particular location has a significant influence on the reconstruction since it severely impacts material procurement. The only materials available on site, according to TEN NGO and Thame Valley Heritage Fund, for which this study was initially developed, were stone, earth and recycled timber [60]. Due to the 1979 World Heritage Site listing, a ban on sourcing local construction-grade timber is in place in the region, forcing reconstruction actors to develop local alternatives or to import the material from neighboring countries.

Due to the evident issue of the shortage of resources and the added limitation posed by the transportation restriction, this case study presents an interesting occasion for reflecting on the consequences of material selection on construction speed.

Due to the remoteness of the reconstruction site, different technologies have been chosen to cover a range from local to imported solutions and to understand the impact of material procurement on the construction speed. The selected technologies, shown in Figure 1 and ranked from those totally available on site to the fully imported ones, are rammed earth, stone masonry, compressed earth blocks (CEB), bahareque, chicken wire with stone, earthbags, Oriented Stranded Board (OSB) cladded timber frame, iron sheet cladded timber frame, and iron sheet cladded steel frame. All of the selected options can be implemented in the area and do not require a consistent amount of electricity or water to be erected.

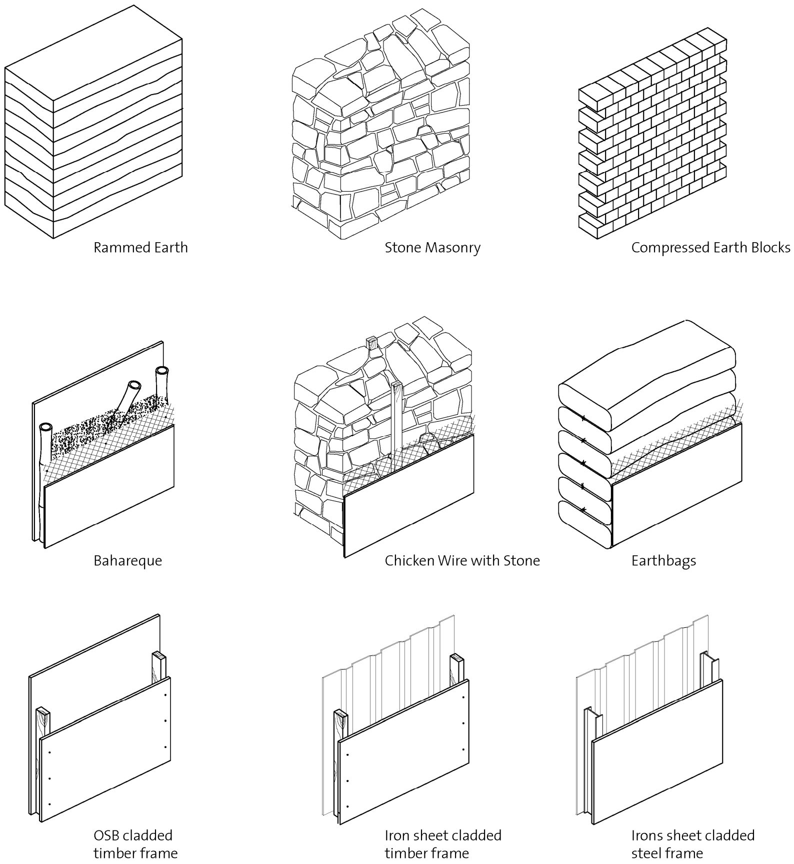

Figure 1.

Representation of the selected technologies suitable for the Thame Valley reconstruction

Material quantity has been obtained by dimensioning the wall for a one storey building development based on construction manuals [61–66], direct experience of the authors due to their background in Architecture in Civil Engineering and referring to documents and drawings of similar self-build structures in analogous contexts [67,68] .

Information on the construction time are obtained through a literature review and consultations with experts, including the direct experience of the first author with self-construction with some of the listed techniques [60,66,69–73]. In more detail regarding material procurement time, non-local materials can indeed be transported on site via a 2-day walk. Specifically, the maximum amount of weight per trip was set as 40 kg and the bulk dimension of the transported items as 250 cm x 60 cm, following the indications of Thame sherpa heritage fund [74]. The speed of construction was then measured in working days per person over square meter of wall (person*day/m^2). This approach has been used in other studies [75] and is a simplified way of looking at construction speed in a purely linear manner. This method is consistent with the LCA approach as it also considers the environmental impact from a linear point of view [76]. Cost estimation has been obtained with reference to Indian market prices at the time of the reconstruction. This is due to consultation with experts locating onsite and operating in the Thame Valley in Nepal at the time of the research [74,77] . The reference to the Indian market has been recommended due to the lack of information available online on the Nepalese context, and to their usual assimilation to the neighboring Indian market. The unit adopted for the economic cost assessment is USD per square meters of wall built ($\$/\text{m}^2$) [60]. In case of a discontinuous structure (ex. Technology Bahareque or OSB cladded timber frame, the cost has been calculated for a larger surface in order to include and distribute the cost of the discontinues element in it, and then divided in order to obtain the cost per square meter of wall built.

The material inventory is shown in Table 1 and displays the building materials adopted to build one square meter of wall according to the different technologies. The amount of each material (kg of material per square meter of wall built) and its origin are presented per technology.

	Material type	Wall (kg/m^2)	Origin
Rammed Earth	Earth	810	L
Stone masonry	Rubble	832	L
	Cement mortar	175	I
Compressed earth blocks	Earth mix	259	L
	Lime	36.22	I
	Clay plaster	51.38	L
Bahreque	Bamboo	7	I
	Earth	160	L
	Chicken wire	0.62	I
	Cement	19.64	I
	Sand	58.91	I
Chicken wire with stone	Timber	6.43	I
	Rubble	832	L
	Chicken wire	0.62	I
	Clay plaster	104	L
	Lime putty	14	I
	Sand	45.6	I
Earthbags	Earth	920	L
	Earthbags	2.30	I

	Barbed wire 4 points	0.89	I
	Chicken wire	0.62	I
	Clay plaster	103.8	L
	Lime putty	14	I
	Sand	45.6	I
Timber frame + OSB	Timber	7.6	I
	OSB board	46.8	I
	Rockwool insulation	7	I
Iron sheet with timber frame (imported)	Timber	7.6	I
	Iron sheet	4.74	I
	Insulation (OSB) board	18	I
Iron sheet with timber frame (local)	Timber	7.6	L
	Iron sheet	4.744	I
	Insulation (OSB) board	18	I
Iron sheet with steel frame	Steel column	8.09	I
	Iron sheet	4.74	I
	Insulation (OSB) board	18	I

Imported = I vs Local = L

Table1. Materials inventory per technology

2.2. Scale 2: Shelter Unit

The assessments of the scale of the building are based on the IFRC data collected in the two documents [78,79] related to shelters delivered worldwide between 2004 and 2011. The shelters considered for the assessment have been implemented in the following countries: Afghanistan (1), Bangladesh (2), Burkina Faso (3), Haiti (4), Indonesia (5), Pakistan (6), Peru (7), Philippines (8), Sri Lanka (9) and Vietnam (10). Shelters have been named according to their main building material (B for Bamboo, C for Concrete, W for Wood and S for Steel) and the country of implementation (Figure 2).

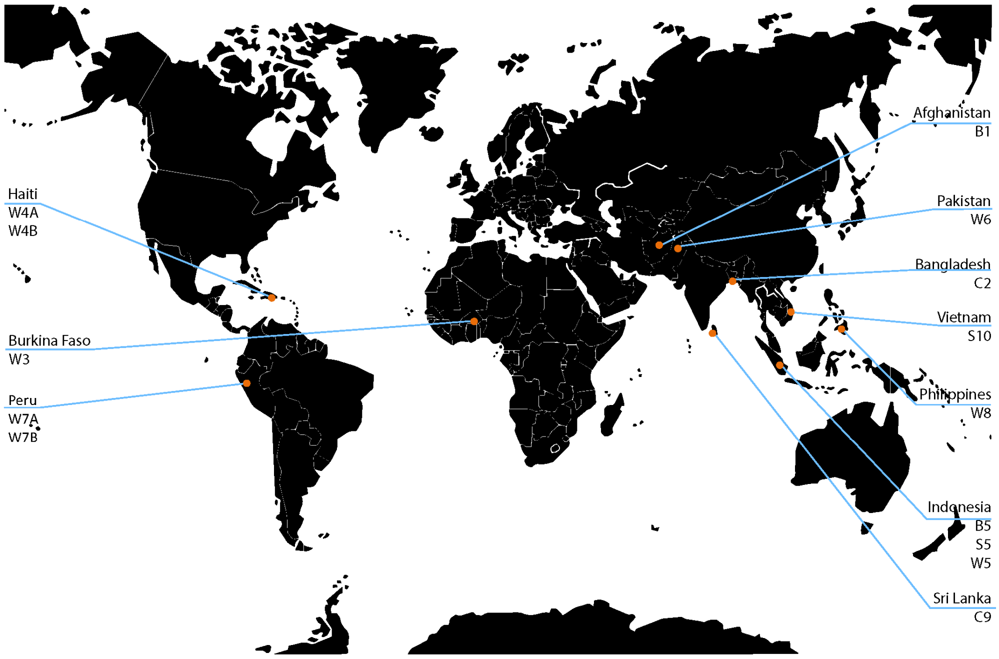

Figure 2. Locations of IFRC shelter projects

The single-family-use shelter designs are different, as are their building technologies, mainly based on bamboo, concrete, steel or wood structures. For each of the shelters, the total amount of materials and detailed material inventories were given, together with material origin, which are presented in Table 2. The ratio of imported materials was calculated over the total amount (kg/kg), and expressed as a percentage. Details on the construction time were also available from the IFRC reports and described the number of working days per team, as well as the number of team members. This information was adapted into the unit of person*day/m^2 as a way to compare the different shelters. Information on the cost was given in Swiss Francs (CHF).

main constructive material		bamboo		concrete		steel		wood								
ID		B5 *	B1 **	C2 **	C9 **	S5 *	S10 *	W5 *	W6B *	W7A *	W7B *	W3B **	W4A **	W4B **	W4C **	W8 **
disaster		earthquake	conflict return	cyclone	civil conflict	tsunami	typhoon	earthquake	flood	earthquake	earthquake	flood	earthquake	earthquake	earthquake	typhoon
year		2009	2009	2007	2007	2005	2004	2009	2010	2007	2007	2009	2010	2010	2010	2011
location		Indonesia	Afghanistan	Bangladesh	Sri Lanka	Indonesia	Vietnam	Indonesia	Pakistan	Peru	Peru	Burkina Faso	Haiti	Haiti	Haiti	Phillipines
type of shelter		trans.	em.	core	core	trans.	trans.	trans.	trans.	trans.	trans.	em.	trans.	trans.	trans.	trans.
covered living space (m2)		24	38.7	14.4	19.6	25	30.2	18	24.5	18	18	15.66	21	17.6	20	17.8
construction time per team (days*ppl)		12.3	36.0	17.5	16.3	16.9	18.0	10.0	4.0	4.0	8.0	12.0	22.5	24.0	70.0	25.0
project cost (Chf)		330	820	1822	650	5100	1500	500	421	560	340	476	2300	5430	2500	421
amount 0f material (kg)	total (kg)	2389	176	3328	3727	2792	15215	1530	8617	6326	4542	6818	7110	2948	6744	2476
	bamboo (kg)	442.7	8.44	590	0	0	0	7.1	0	0	29	0	0	0	0	346
	steel (kg)	2.2	0	879	142	978.3	7941.2	3.9	190	93.1	78.1	0	183.1	135.6	0	175
	timber (kg)	0	38.37	148	122	956.6	76.3	324.1	215.6	1643.1	101	139.7	790.97	1413.4	1012.4	581.1
	bricks (kg)	1087.5	0	1265	0	0	0	0	7991	0	0	0	0	0	0	0
	concrete (kg)	856.8	0	446.3	3449	856.8	7197.1	1066.2	0	4590	4284	6578.6	6136.12	1399.4	5731.2	1373.6
	plastic sheets (kg)	0	128.94	0	0	0	0	3.4	139	0	50	99.5	0	0	0	0
	others	0	0	0	14[A]	0	0	124.8[B]	81[C]	0	0	0	0	0	0	0
% transported over total materials		0%	100%	0%	0%	100%	51%	0%	4%	0%	3%	1%	100%	100%	100%	0%

Document source: *IFRC2011 **IFRC 2013

Legend: transitional,emergency, core shelter, ^{A} bitumen ^{B} palm leaves ^{C} polystyrene foam

Table 2. Shelter material inventory

Correlations between the ratio of imported materials, construction speed and cost were then investigated.

2.3. Scale 3: Post-disaster settlement

Where data were available, the same shelters were the subject of further study at the settlement scale. Details on the settlement projects are obtained by consultations of diverse reports from the Shelter Cluster (Table 3). Due to the extensive research that occurred in the affected areas of the 2004 Indian Ocean tsunami, the reconstruction program in Aceh became a relevant benchmark for post-disaster shelter delivery on a large scale [24,25,35,80]. For this reason, the case study of Aceh (Indonesia) has been added to the trend.

ID	location	report name	report number	authors
B5	**Indonesia**	Indonesia Yogykarta Earthquake Operations Update	11, 12, 13, 14, 15, 16, 17, 24	IFRC
C2	**Bangladesh**	Bangladesh Cyclone SIDR Operations Update	10, 11, 12, 13, 14, 15	IFRC
C9	**Sri Lanka**	Sri Lanka: Support for internally displaced people Burkina Faso Floods Final Report	3, 8, 10, 14, 16, 18	IFRC IFRC
W3	**Burkina Faso**	Burkina Faso Floods Operation Update	3, 4, 5, 6	IFRC
W4A/ W4B	**Haiti**	Haiti Earthquake Operations update Haiti Earthquake Operations Update 12 months progress Haiti Earthquake Operations Update 18 months progress	6, 10, 13, 15, 22, 26, 27, 30, 31	IFRC IFRC IFRC
W5	**Indonesia**	Indonesia West Sumatra Earthquake Operations Update	10, 11, 12, 14, 15, 17	IFRC
W6	**Pakistan**	Shelter Projects 2013-2014		UNHCR, IFRC, UN-HABITAT

W7A	**Peru**	Peru Earthquake Operations Update	4, 5, 6, 7	IFRC
		Bangladesh Cyclone SIDR Final Report		IFRC
W8	**Philippines**	Philippines Typhoon Operations Update	9, 11, 13, 14, 15, 17, 18	IFRC
		Philippines Typhoon Final Report		IFRC
	Aceh	Lessons from Aceh		Jo da Silva, ARUP International Development

Table 3. Post disaster settlements reports

The assessment at the settlement scale considered project cost and construction time over the elapsed project delivery among the overall settlement completion. Due to the different scales of the settlements considered, the elapsed time has been expressed as a percentage over the total project conclusion. The influence of material procurement has been studied by dividing the shelters into two groups: locally based and imported. The correlation between project cost, construction time and material procurement was then plotted.

3. Results

The results are presented in the following sections according to the three different scales of the assessment (Constructive technology, shelter unit and settlement scale).

3.1. Scale 1: Constructive Technology

The results for material procurement (X-axis), construction speed (Y-axis) and cost (secondary Y-axis) are shown in Figure 3.

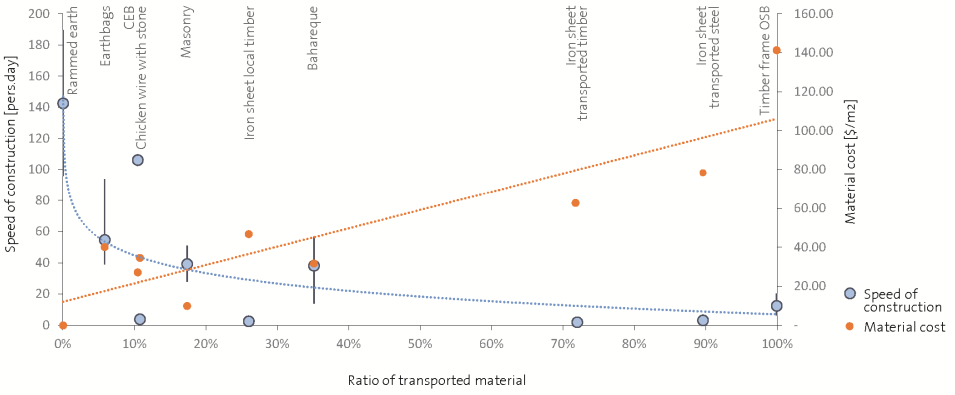

Figure 3. Construction time and project cost vs. ratio of imported material at the building element scale

From this figure, it is possible to see that local technologies such as Rammed earth have a slow construction speed and some of the lowest values for cost. The opposite trend can be observed for the global materials, ranked as the fastest and most expensive. Due to the logarithmic trend of the construction speed, it is possible to observe that a minimum input of imported materials, as in the case of Compressed Earth Blocks, Chicken wire with stone, Masonry or Bahareque, allows for an important reduction in the construction time while still maintaining its affordability. In contrast, the economic cost of the construction increases linearly when moving from local to imported technologies. At the material scale, we can then conclude that a limited amount of imported material allows for a drastic improvement in the construction speed without significantly impacting its economic cost.

Scale 2: Shelter Unit

At shelter unit scale, the correlation between material origin, construction time and project cost is presented in Figure 4.

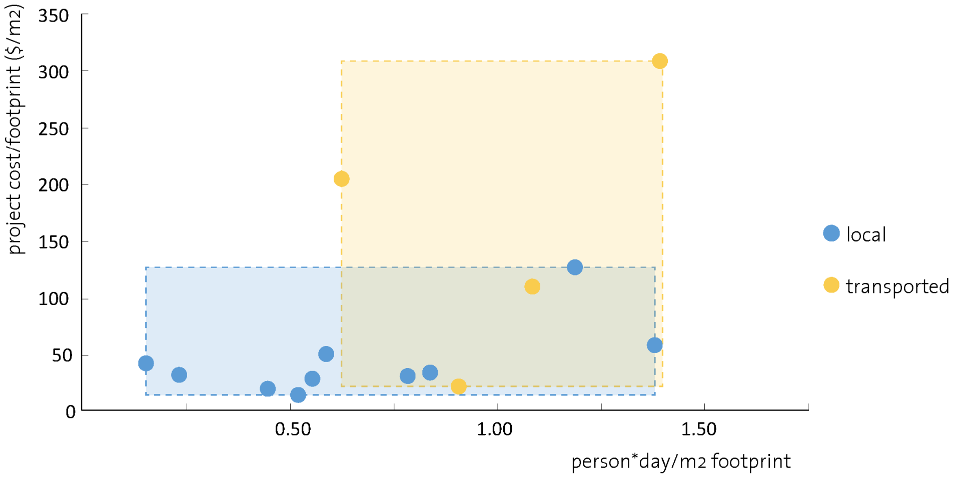

Figure 4. Construction time, project cost and ratio of imported material at the shelter scale

It is not possible to establish a clear correlation between the material origin and its time and cost performance due to the trend. Shelters mainly built with local materials (in blue in the figure) here show both a low project cost and a slow construction speed. Local materials seem to be more effective from a cost perspective, as well as for their speed efficiency. Imported solutions instead cover a broader range from a cost perspective, as indicated by the position and shape of the yellow box, but a more homogeneous result in terms of time delivery. Due to the lack of clear correlation between material procurement and speed at the shelter unit scale, further analysis has been carried out to identify the drivers of construction speed at the current scale.

The shelters considered for the analysis differ in materials, type of constructive techniques, building details and cost. These aspects have been examined to identify eventual factors driving the construction speed since the analysis on the shelter cost and material procurement did not show any significant correlation.

Considering the shelter in its complex building phase, and due to the difference in the design presented by the case studies, the shelters have been grouped according to their footing types into four categories (bucket, prefabricated, slab, and in-situ column). No correlation has been identified between these different constructive solutions and the speed of delivery. It is thus possible to say that the type of footings does not significantly drive the construction time at the shelter scale (detailed information is available in the Supplementary Material).

Considering then the shelter unit under the lens of ease of assembly, shelters have been further analyzed according to their total number of constructive elements, here referring to building elements requiring assembly on site, as individual timber pieces joint together in one truss or bamboo floor joists and bracing to be combined in the floor structure . Once again, the variation is large and does not show any relevant trend (details are available in the Supplementary Material).

Even though the shelters differ in many aspects, all of them are based on the principles of simple design, consisting of a one-floor single-family shelter based on a single room, aiming for a fast replicable solution, and easy to implement by non-trained labors. Despite that, the element of the roof is the one that most shows variations in terms of design and the number of pitched elements, ranging from a low slope flat roof to gable, hip and mansard types, making it an interesting object to be considered in the study due to its possible impact on the construction time. The shelters have thus been ranked according to the number of structural elements composing the roof and studied in correlation with the construction time, as shown in Figure 5. The number of roofing element is referring to the number of building elements as bracing bamboo elements or timber trusses components requiring on site processing and assembling at height, a process that is naturally slower than ground work, and for this reason significant for the study.

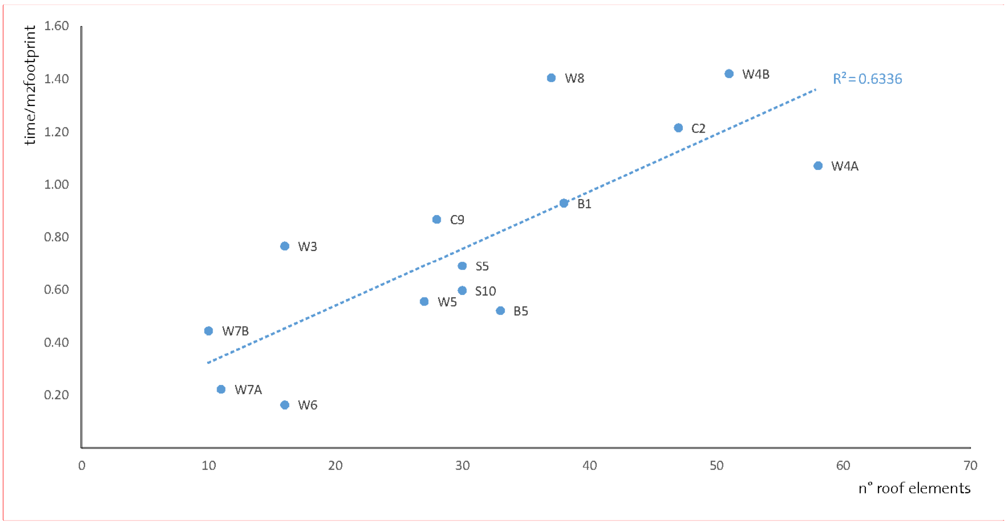

Figure 5. Number of roofing elements vs. construction time (shelter scale)

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Figure 5 clearly shows that the roof design has a strong impact on the time of delivery of the full construction unit.

To conclude, it is possible to say that, at the shelter scale, the ease of assembly of the roof, based on the complexity of its design, has a major impact on the construction speed of the shelter.

Beyond that, it is also shown that the main speed driver identified at the shelter scale, consisting of material origin, has no particular relevance at the current scale, where it becomes secondary compared to the roof design.

3.2. Scale 3: Post-disaster settlement

The assessment then considers the speed and cost of delivery of the post-disaster shelter at the settlement scale in relationship to the material procurement.

As already known from previous works [35,81], the settlement construction completions follow an S-Curve trend, divided into the three consequent phases of Build Up, Steady State and Run Down. Based on the database provided by IFRC and additional reports on the progress of the assessed projects, it was possible to draw the trend of the settlements development according to their material procurement [82]

In addition to the three phases identified into these previous works, this study seems to show that the origin of the materials has an influence on the shape factor. Actually, on figure 6, representing the percentage of elapsed time on the X axis and the percentage of completed shelters on the Y axis, shelters have been grouped according to their material origin. It is so possible to observe that the Build-up phase is shorter and that the Steady state curve is steeper for local shelters. These two observations result in a faster take-off for local shelters, followed by a boosted speed during their project running time.

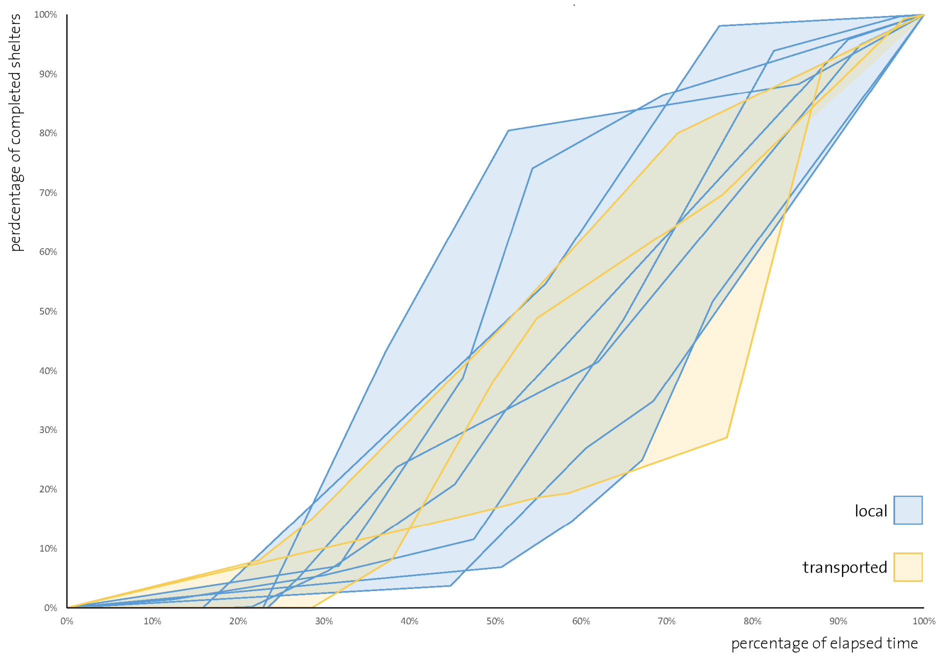

Figure 6. Shelter settlements construction development over time

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It is then possible to state that, at the settlement scale, the material origin becomes relevant again, as shown at the material scale. The impact of the roof design at this stage is, instead, secondary, as the shelters with less roof elements do not correspond necessarily to the ones with a steeper Build-up curve in Figure 6. The impact of the complexity of the roof design, preponderant for the building unit, is still present here, and it can, in fact, explain the non-optimal performance of the shelters C2 and W5 .

Kommentar [CG3]: should I add the shelter numbers in the graph so to make this statement more clear?

4. Conclusion and Discussion

Post-disaster reconstruction necessarily confronts the issue of speed of delivery due to the urge posed by the emergency affecting the displaced population, and by the tendency of the local population to resettle rapidly in the local disaster prone areas without improving the construction performance.. This paper, based on data provided by IFRC and consultations from experts, looked at how resource procurement (*local* or *global*) affects the speed of shelter delivery at three different scales: building technology, shelter unit and post-disaster settlement.

The results show that different drivers of speed of delivery can be identified at each scale. When dealing with the project design at the scale of the constructive technology, it is relevant to consider mainly local materials together with an appropriate input of industrialized ones (approximately 10-20%), in order to achieve a faster construction without heavily impacting on the cost. This driver, however, becomes secondary at the higher scale of the shelter unit, where the complexity of the roof assembly emerges as the main factor affecting the construction speed. It is possible to say that an appropriate roof design has the capacity to boost the speed at the shelter unit scale significantly. Finally, when managing the construction of multiple shelters, the material supply for the entire building (walls and roof elements) once again becomes a priority for reducing the construction time.

On a more practical level, according to the scale of the project (construction system, shelter unit or settlement scale), it is then necessary to consider the relevant driver to achieve fast construction prior to getting started with the project design.

Nevertheless, it is necessary to keep in mind that the study assessed reconstruction shelters delivered worldwide. This means that significant parameters of a post-disaster reconstruction success as climatic, social and geographic conditions characterizing their construction development and choice differ case by case. The lens under which post-disaster reconstruction have been studied in this work is uniquely the one of construction speed, due to its relevance in emergency construction and to the lack of consistent studies in this direction. Even so, it is recommended to investigate the complementing local factors influencing shelter delivery as well, and to combine them with the here provided technical assessment in order to achieve an integrated understanding of the construction dynamics.

Despite the limitation of the study due to the different context of the assessed projects, key findings for targeting reconstruction speed can be drawn by this study, and should be considered in the planning and design phase of post-disaster reconstruction projects. According to the scale of the project, different criterias regarding design and material selection should be considered by engineers, architects and planners in order to achieve fast shelter construction. The work shows the validity of a multiscale assessment, enabling policy makers for recommendations addressing different stakeholders involved in post-disaster projects.

Despite the extreme complexity characterizing post-disaster reconstruction, kowing the different drivers’ impacts on the construction speed at the three scales sets a technical solid basis for efficient design guidelines towards rapid reconstruction.

5. Acknowledgment.

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Abstract:

Abstract

The effects of urbanization and climate change are dangerously converging. The most affected populations are the urban poor, settled in informal settlements vulnerable to increasingly frequent disasters. This severely contributes to the existing housing gap of these regions, already struggling with housing demand. The speed of shelter delivery becomes key for an efficient response in order to prevent spontaneous informal resettlements on unsafe lands. The present study aims to understand the impact of material choice on post-disaster shelters delivery through a multiscale analysis of construction speed. The scales considered are: Constructive technology, Shelter Unit and Post-disaster settlement. At the the Constructive technology scale, nine different reconstruction solutions for the Nepal earthquake are compared, covering a range from local to industrialized. Successively, twelve shelter designs by the International Federation of the Red Cross have been studied under the same lens at the Shelter unit scale and for Post-disaster settlements. The study identifies a clear correlation between material procurement and speed at the constructive technology scale. At the shelter scale, this correlation becomes secondary and construction time is seriously impacted by the complexity of roof design. Moving to the settlement scale, the choice of local over industrialized materials seems to drive the speed again. The study indicates how a multiscale approach is necessary to analyze the impacts of material selection, providing efficient guidelines for post-disaster reconstruction. Beyond that, it highlights that effective reconstruction can be developed with diverse materials, but its emergency responsiveness can seriously be compromised by a non-appropriate design.

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