Wood-based 3D printing for space innovation in emergency and social housing production

by

Rodrigo Cepeda

Architect, Catholic University of Chile, 2000

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ADVANCED STUDIES IN ARCHITECTURE

in

THE FACULTY OF GRADUATE STUDIES

(Architecture)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

October, 2012

Abstract

Since the 1900s, urban population settlements have experienced explosive growth.

To respond to this urban population growth, suburban areas and industrialized housing production were developed. However, today, a series of negative impacts from these solutions has been detected.

While suburban areas create big morphological changes to the city, causing problems of transport, fragmentation, and social connectivity, industrialized prefabrication methods result in a mass repetition of identical houses that elicits social and physiological problems of individuality and community belonging.

The case of Chile is notable because of its 86% urban population and its stable social housing response to homelessness. In addition, the country is subjected to frequent natural disasters, and the government has to respond quickly with emergency and social housing solutions.

However, calls to the attention that being an exporting country of forest products, wood is not considered a building material solution for long-term houses.

This research analyses the historical and current development of emergency and social housing in Chile, the country's forestry production, and the characteristics of local wood products.

Advantages and disadvantages are examined along with highlighted case studies, and a new emergency and social housing architectural strategy is proposed.

To meet this need for massive emergency and social housing, a flexible, fast, and optimized building system is required.

Digital fabrication technologies are presented as a basis for rethinking mass housing production, focusing on a prefabricated full scale 3D printing process; a parametric manufacturing relationship between structure, thermal performance and material composition is proposed.

In the initial stage with structural simulations, this research explores the optimization possibilities of the architectural elements with the relationship proposed, and suggests possible applications and future developments.

Table of Contents

List of Figures

Acknowledgements

I would like to thank all of the staff of the School of Architecture and Landscape Architecture, including special thanks to Greg Johnson.

Also, I would like to thank my committee members, James Olson and Annalisa Meyboom, for their guidance and support.

Finally I would like to thank my supervisor, Oliver Neumann, who provided his time, insight and guidance along this research.

Dedication

To Tomás

1. Mass Housing Production

Since the beginning of the 20th century, urban population settlements have experienced explosive growth. In 1900, the world urban population was 14%, now it is over 50%, and by 2030, it is projected to be 61% (Freire 2007).

With an estimated population of 17,000,000, the case of Chile is notable because the urban population is 86%, with 40% concentrated in Santiago, the capital (UNICEF 2003) ("fig.1").

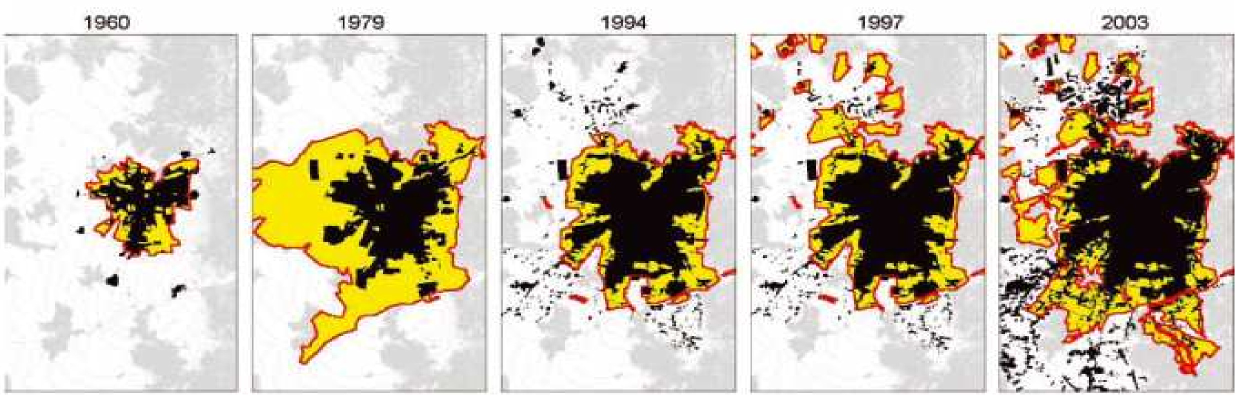


Fig.1: Urban sprawl of Santiago de Chile in the last 50 years. Black areas represent built zones, and yellow areas represent the city limits according to the Building Code.
Because land is cheap outside of the urban limits, in 1981, in order to encourage social housing construction, a law approved the construction of social housing projects beyond the boundaries of the city. As indicated, in 1994 and thereafter, there are several black dots outside of the yellow area.

In order to house this mass immigration in Chile and in countries with rapidly increasing urban populations, architects and urban planners must overcome the challenge of large- scale housing production.

To meet this challenge, urban planning designers started developing large suburban areas, while architects, following the example of the aircraft and automotive industry, adopted an industrialized production process.

From the beginning, this new approach predicted benefits to the city like urban decongestion, lower residential densities and greater home ownership; however, despite numerous and continuing projects, suburban areas ended up creating big morphological changes to the city, causing serious problems of transport, fragmentation, and social connectivity.

Also, the use of industrialized prefabrication methods resulted in the production of houses that look like traditional suburban dwellings; but they were no more than container-sized modules with a few on-site finishing touches. People were living in houses that were like “boxes”, all identically designed and placed together. This development created social and physiological problems of individuality and community belonging (“fig.2”).

Fig.2: New social housing project in San Bernardo, Santiago de Chile, 2012. The project is located in the periphery areas of the city and is attached to negative externalities, in this case, the North-South highway.

The same urban planning and architecture strategy developed as a solution to rapid urban population growth, is now identified as the suburban crisis. To resolve this crisis, one of the theoretical perspectives of sociological studies points to a suburban innovation on physical design (Baldassare 1992).

The susceptibility of Chile to natural disasters aggravates this problem, as once in a while, a group of families can lose their houses in seconds, and the government must be prepared to provide a time-sensitive solution.

But even 60 years after the beginning of mass housing production, the country's approach has not changed.

How can we architecturally improve the process to house homeless people?
What are the housing politics involved in mass housing production?
Which building technologies could address the challenge?

1.1. Mass Social Housing Production in Chile and the Industrialization Process

There are two main categories of mass housing production in Chile. One is supported, provided and coordinated by the government, and the other is offered by the church and by nonprofit institutions.

1.2. The Government as a Social Housing Provider

The mass housing production process started in Chile between the 1940s and 1960s. During this period, the government recognized the number of homeless people in the country (400,000) and stated that it would create a national housing program by establishing the National

Housing Corporation (1941). The government, moreover, promulgated the first Chilean Construction Code (Ministerio de Vivienda 2010).

Also, to promote the creation of houses and industry, the government developed laws that encouraged the private construction sector to participate in the housing process, with tax reductions for social housing construction. However, the construction of social housing during that period was low, with an average of 9,400 units per year.

In the next decade, organizations involved were redefined and improvements in laws were made, leading to an average of 27,000 units of social housing constructed every year for the first 6 years.

Despite the improvements, in 1960, 31 commercial prefabricated systems existed in the country, but the government did not consider them viable solutions for mass social housing production.

However, for the first time, the National Housing Corporation called for a competition of “Experimental Houses” (industrialized systems) in two neighborhoods in Santiago de Chile that same year (Bravo 1974) (“fig. 3”).

Here, the Government recognized that to overcome the homeless challenge, innovations in the building systems were necessary, and that industrialized prefabricated systems were among the answers.

In the early 1970s, studies calculated that the social housing prefabrication industries were able to produce 60,000 units per year, although only between 4% and 8% of their production capacity were used.

Without succeeding in reducing the population of homeless people in the country, a new government, between 1970 and 1973, promoted industrialization and prefabrication methods with the creation of The Department of Industrialized Housing as a new branch of the National Housing Corporation. A few more initiatives were created to promote industrialization, but the program failed. While 90% of the houses were built using industrialized bricks, the houses did not use any prefabricated system.

In 1973, the subsequent military government established a successful housing program that created an average of 30,000 units per year, which is the basis of the housing program that exists today.
During this 17 year period, prefabrication and industrialized methods were not part of the discussion on social housing.

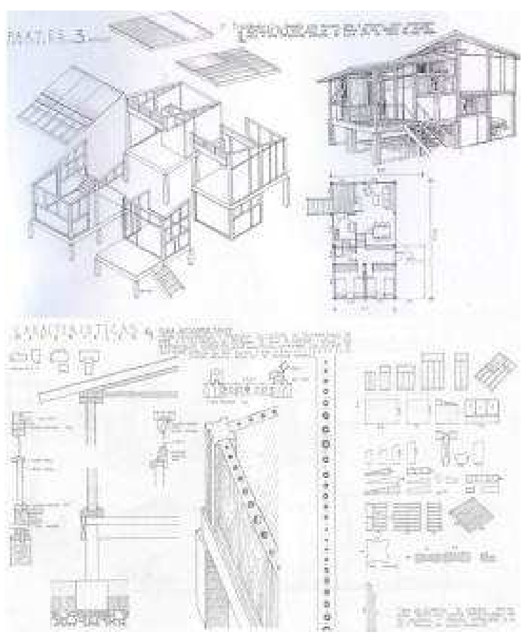


Fig.3: Mena House, 1970: A prefabricated module system. The module was made of wood- based wall panels, with 2mm veneer on both sides of the walls. The walls were made of medium density fibres (press 175*C, pression 22 Kg/m2) with interior holes for insulation, and used less material. In addition, the house has a passive ventilated temperature control system.

Industrialized prefabricated systems were moved to the second house market, and with the big economic crisis of the 1980s, almost all of the prefabricated industries disappeared.

Today, Chile is one of the few Latin American countries that have political support for stable low income housing, but 90% of the houses are made out of brick masonry, and prefabrication methods are not explored as part of social housing efforts in Chile.

The State and the private sector, through a series of initiatives, have managed to sustain constant construction during the last 35 years, coming to an approximate average of 110,000 housing units created in the last ten years, of which 60,000 were social housing (Navarro 2005). However, the remaining housing need still exceeds 500,000 units (Ministerio de Vivienda 2004).

Homeless people, in order to obtain their social house, have to fill out a survey, and would qualify based on several stipulations, the most important being whether any family member is employed. The families who qualify are asked by the government to save and deposit US $450 which would be put into the project, and to group into a committee.

Committees comprise families in the same situation, and for the private construction companies, a project becomes profitable when it involves 30 or more families.

In addition to the family's saving, the government will provide the purchase of the land and approximately US $16,000 per house to be built. The design of the houses must meet a minimum program, with minimum defined sizes for spaces, and a future expansion.

Over time, the policies appear to have reduced the enormous deficit in the quantity of housing, but have not addressed the problems of quality and durability in Chilean housing development. However, the government now recognizes the need for an improvement in the quality of the residential solutions, putting emphasis on the energy efficiency performance of the houses, and incorporating thermal regulation into the housing design requirements.

Thermal regulation became effective in the year 2000. At first, thermal regulation standards only required insulation for the roof of the house, but since 2007, these guidelines have incorporated a minimum thermal performance for the complete envelope of the house, according to the specific geographic location where the project will be located ("fig. 4 and 5").

Tabla I.3.1 EXIGENCIAS TÉRMICAS A ELEMENTOS ENVOLVENTES DE LA VIVIENDA CONTENIDAS EN LA RT.

ZONA TÉRMICA	TECHUMBRE		MUROS		PISOS		VENTANAS % Máximo de ventanas respecto a parametros verticales de la envolvente		
							VIDRIO MONOLÍTICO	DOBLE VIDRIADO HERMÉTICO	
	U W/m^2K	Rt m^2K/W	U W/m^2K	Rt m^2K/W	U W/m^2K	Rt m^2K/W		3,6 W/m^2K >= U > 2,4 W/m^2K	U <= 2,4 W/m^2K
1	0,84	1,19	4,0	0,25	3,60	0,28	50%	60%	80%
2	0,60	1,67	3,0	0,33	0,87	1,15	40%	60%	80%
3	0,47	2,13	1,9	0,53	0,70	1,43	25%	60%	80%
4	0,38	2,63	1,7	0,59	0,60	1,67	21%	60%	75%
5	0,33	3,03	1,6	0,63	0,50	2,00	18%	51%	70%
6	0,28	3,57	1,1	0,91	0,39	2,56	14%	37%	55%
7	0,25	4,00	0,6	1,67	0,32	3,13	12%	26%	37%

Fig. 5: Climatic Zoning in Chile. Chilean Building Code.

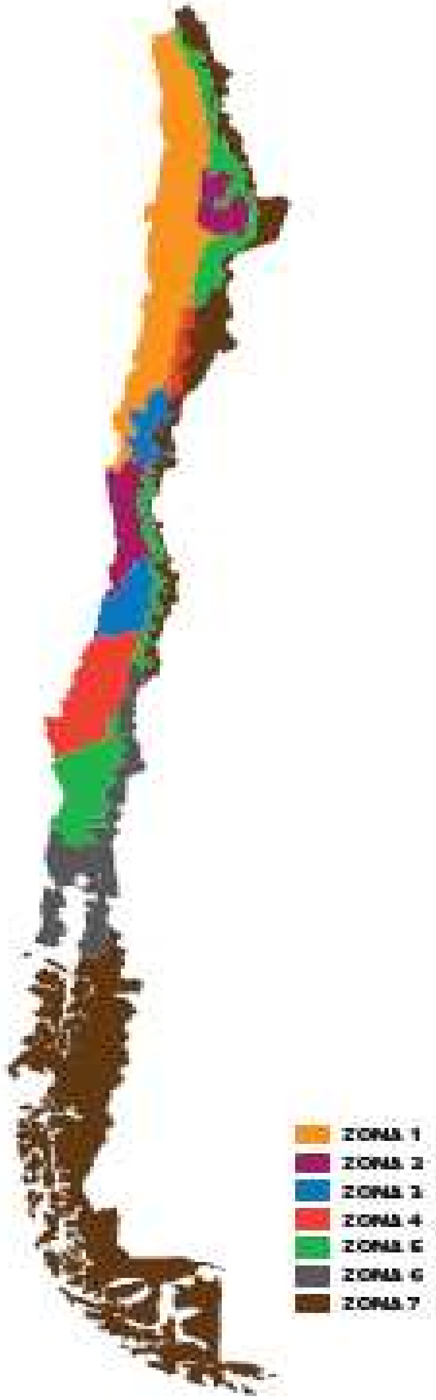


Fig. 4: Thermal Resistance or U value requirements for the envelope of the houses in Chile, Chilean Building Code.

While experts considered the thermal requirement acceptable for roofing, on the contrary, they found that the requirements for walls under these new regulations were still insufficient. They also agree that the variation of the thermal requirements according to the geographical location of the project is an enormous advancement, but the zoning is still not accurate enough (Bustamante 2009).

Today, as a result of the mass social housing production process and its needs, most of the houses built have dimensions that vary between 40 and 45m2 with an interior height of a flat 2.3 meters. The most common material definitions are 150 mm of industrialized wall bricks for the perimeter and light metal frame for interior walls and roof structure. Also, the houses have 100 mm of insulation over 10 mm of gypsum board ceiling.

On the other hand, these neighborhoods are developed in the peripheral areas of the city, where land is cheap, but far away from the workplace, schools and social networks of families.

The development of this mass housing production system does not allow modifications, and finally, the houses and neighborhoods end up designed under a repeated rigid typology (“fig. 6”).

Today in Chile, almost all of the social housing projects are built on site and are made under the policies, design and material specifications described.Furthermore, Chile is a country that is susceptible to natural disasters. If a natural disaster happens and some families lose their houses, the government sets in motion special emergency plans. In the first stage, the government organizes the supply of emergency houses, and in the second stage, provides a permanent social housing solution.

Fig. 6: The most common detached and attached Social house typology built in Chile. The detached house has 41m2 and a possible future addition of 12m2. The attached house has 45 m2 and a 12 m2 possible future addition.

The government emergency plans involve two different types of social mobility: On the one hand, if the families own the land where their house collapsed, the government will first build an emergency house on each family´s property, and then, a permanent social house solution. On the other hand, if families do not own the land where they lived, the government first relocates them to camps in an emergency house solution, with a commitment to deliver a permanent social housing solution as soon as possible.

For example, the most recent earthquake in Chile, on February 27th of 2010, left 80,000 people homeless. To quickly house these newly homeless people, the government required the construction of 20,000 emergency houses.

The construction and supply of these emergency houses took 5 months, and 2 years afterward, only 30% of the final solutions have been completed.

The reasons for the slow response of the authorities in the case of landowners, is due to the enormous complexity of building specific individual projects in place of collapsed houses.

In the case of the families that do not own the land where they lived, the government faces the challenge of finding available properties in the same neighbourhoods where the families lived before the earthquake, because families do not want to be moved to other places, especially to the periphery of the city (“fig. 7”).

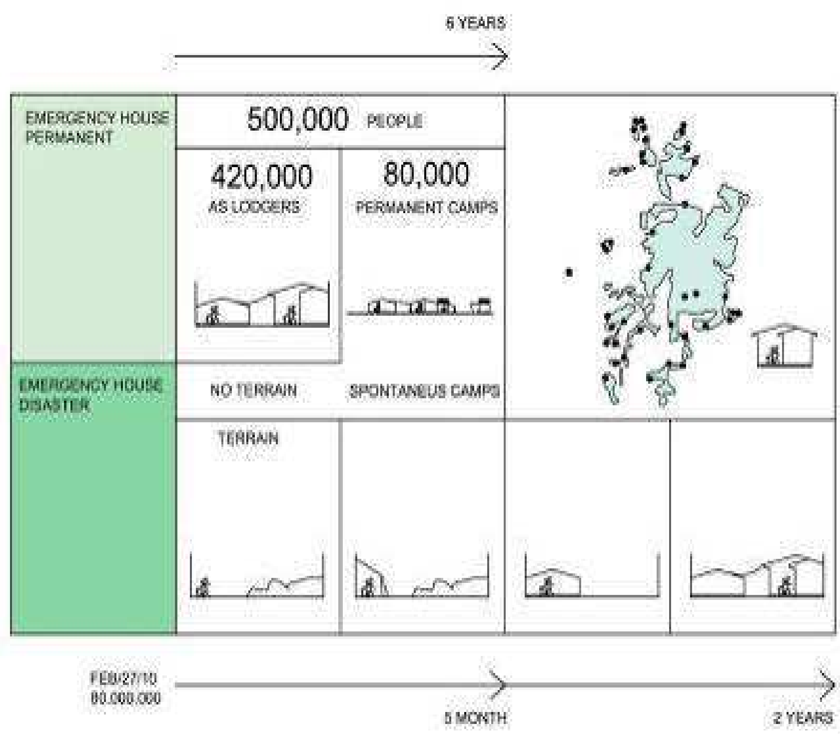


Fig. 7: Emergency and Social Housing Mobility in Chile.

1.3. Self-Imposed Challenge for the Church and Nonprofit Institutions.

In the 1940s, at the same time the government assumed the responsibility of supplying housing for homeless people, the number of homeless families started to increase rapidly.

The actions of the government to provide social housing for homeless people, in most cases, were slow, and as a consequence of these delays, spontaneous neighborhoods of emergency houses and makeshift abodes emerged in the city.

In 1958 “El Hogar de Cristo”, a Catholic organization, helped by nonprofit organizations, accepted the challenge of providing shelter for the homeless (Arteaga 2012).

In order to achieve this, the charity organized a low-tech industry for prefabricated wood panels to build 3x6 meter emergency houses, with an approximate height of 2.4 meters.

Using green radiate pine, the houses are made of six prefabricated wall panels, two floor panels and a metallic roof cover (“fig. 8”).

Fig. 8: Emergency house projects do not consider public space configuration.

Despite its simplicity, with 50 years of history and an average of 4,500 units built per year, this emergency housing solution has proven successful in the Chilean context, being for years the one and only mass industrialized building system in Chile (Arteaga 2012).

Since 1960, the design and specifications of "El Hogar de Cristo" emergency house has not changed, being socially recognized as the unique typology of emergency housing solutions in the country.

The majority of families that received this emergency housing solution represent the extreme poverty segment of the Chilean population. This extreme poverty segment lives in urban camps or as guest lodgers in other homes. ("fig..9").

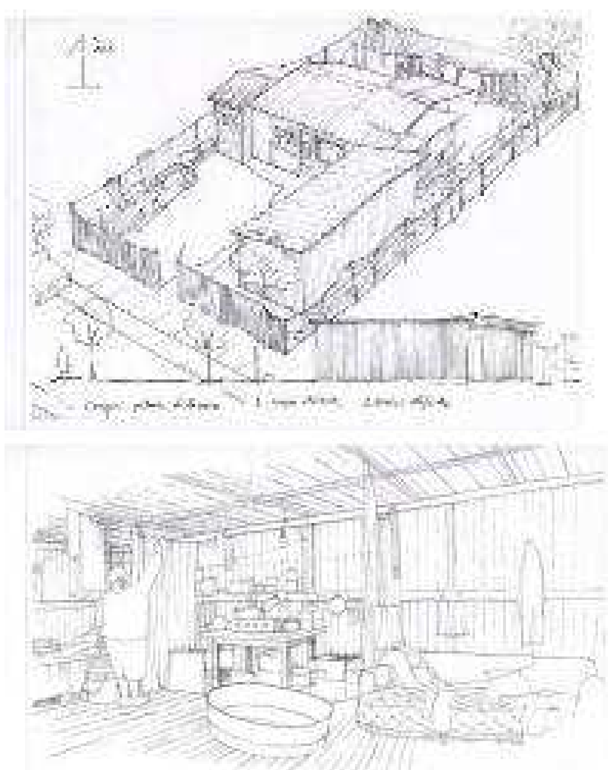


Fig. 9: Interior space of an emergency house and the house lodger situation.

Despite the importance of emergency houses to the families that receive them, the low technical and architectural quality of the houses has been highly criticized (Bustamante and Victorero 2011).

While the emergency house that is provided today was established in 1958 as a minimally decent housing solution for those living in extreme poverty, the poverty in the country has declined from 38.6% in 1990 to 15.1% in 2009, according to the Social Economic Characterization Survey of the National Planning Ministry (Ministerio de Desarrollo Social 2010) .However, the emergency house standards have not been raised to reflect this change.

The continued economic growth that the country has been sustaining for the last 35 years, also supports the hypothesis that poverty has changed and housing standards should improve too (Tironi 2003).

As described, spatially the emergency house is no more than a “Box”, and does not have essential building materials for an appropriate degree of habitability and comfort. And although this emergency solution is often regarded as a temporary situation, in many cases it ends up being a final solution.

Over time, families would build additions with minimal available resources, and without any expert supervision; the houses would end up with spaces that lack sunlight, ventilation and public space considerations.

1.4. Research Premises

For 60 years, the quantity of homeless people in Chile has not decreased.Despite a few opportunities that aimed to improve the construction and quality of social housing and emergency housing solutions with prefabricated and industrialized methods, the final results lacked continuity and had serious deficiencies in terms of durability and habitability.

An important indication of these poor results is the fact that 20% of the families returned from the final social housing solution provided by the government to the urban camp.

Reviewing the history of the massive social and emergency housing production in Chile, and the institutions involved in the process, this research recognizes three aspects that need to be reconsidered.
First, industrialization and prefabrication systems are usually presented as possible solutions to house homeless people, but they have not successfully emerged mainly because of a lack of political support from the government.
Second, families that do not qualify in the survey for the social housing applications are not considered by the government. In the case of Chile, this includes half a million people ("fig. 10").

And third, the social housing process requires a lot of flexibility; however, the architecture of emergency and social housing carries with it enormous social, political and economic complexity, from the design regulations required by law to the final product built by the private construction companies, and the process does not allow modifications or changes.

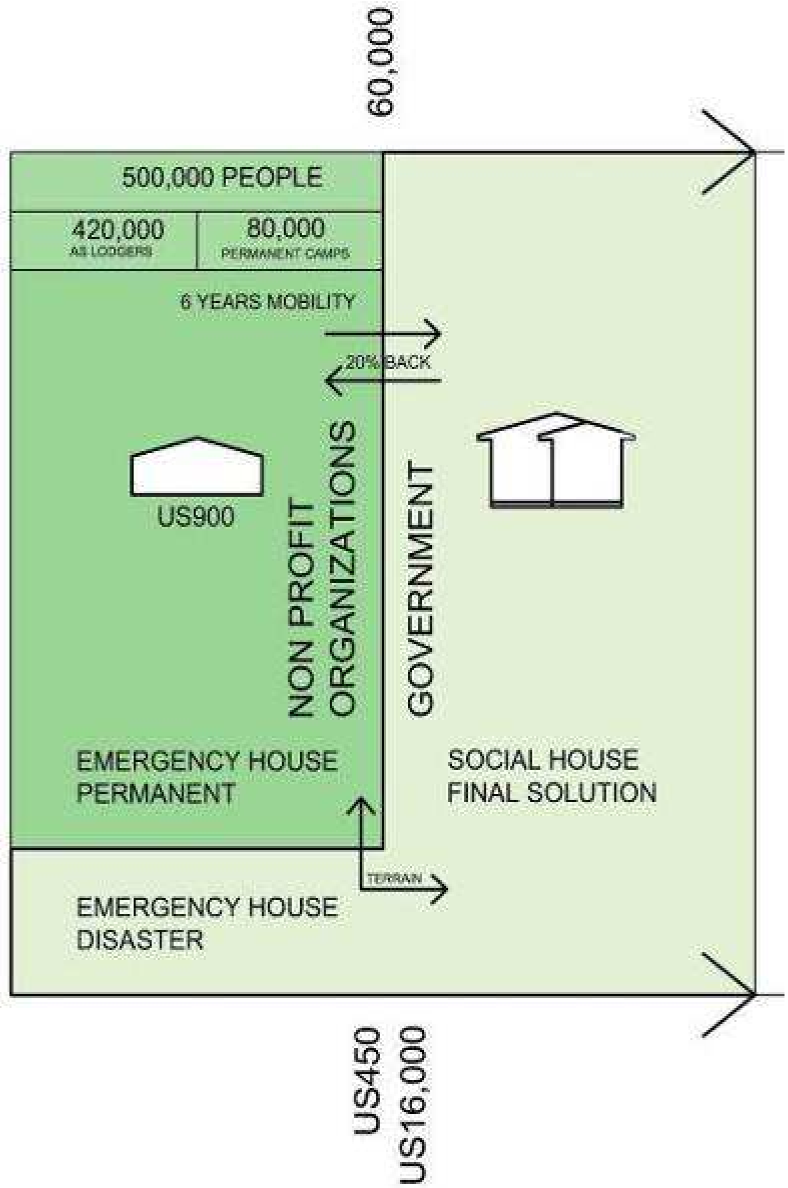


Fig. 10: Chilean Housing Economic Edge: Agencies and Solutions.

Considering these three points, this research recognizes the need for more flexibility in the process for the incorporation of new building systems, flexibility for the incorporation of every homeless person into a housing strategy, and flexibility in the design requirements.

Which characteristics should the new building systems alter, in order to elevate the standard of the housing solution?
How can we architecturally integrate all the homeless people in the process?
Which design requirement should be incorporated into the process of emergency and social housing production?

In the last few years, some good examples of social and emergency housing projects have appeared, providing some approaches to the answers we are looking for.

Notable is the case of ELEMENTAL social housings, and the Modarq – CIDM and REMA emergency houses.

1.5. The Case of Elemental S.A. Social Housing

The ELEMENTAL S.A. architecture office developed a social housing project with the aim of providing a better location in the city, so that families could live closer to where the opportunities are, such as work, health and education.

Also, if the property is in a good location in the city, its price will rise over time, therefore making it a good investment for the families.

In order to counteract the high land values in these locations, the project directors have proposed to put more families in the same location, thereby increasing density.
In addition, the families would receive only half of the size of a house that is usually given in these types of projects, but with a possibility of expansion into a 75 m2 house (“fig. 11, 12 and 13”).

Fig. 11: Quinta Monrroy project. Architecture by ELEMENTAL S.A., 2004. Located in an urban context.

Fig. 12: Quinta Monrroy project. Architecture by ELEMENTAL S.A., 2004. The project considers guidelines for future additions with self-construction methods.

Fig. 13: Quinta Monrroy project. Architecture by ELEMENTAL S.A., 2004. The picture shows the development of self-constructed additions.

1.6. The Case of Modarq – CIDM Emergency House

Modarq - CIDM emergency housing was developed to meet the demands of the earthquake that occurred on Feb. 27 of 2010, in Chile.

This project, under the supervision of the Timber Research and Development Centre of the Catholic University, was presented and built as an alternative solution for emergency houses in rural sectors.

The house, a modular wooden structure, permits several possibilities for future expansions. Also, its enclosure wall has the potential for quality improvement over time. Therefore, what was initially considered an emergency house could become a final solution.

Remarkable in the design of this emergency house is the understanding of the wall as a complex of elements, with specific functions, that together comprise a unit.

Initially, the Modarq – CIDM system considers the structure, the outside finishing, the ventilated air gap and the wind barrier; families, with the help of a guide manual can install insulation, a vapor barrier and the interior finishing on their own (“fig. 14, 15 and 16”).

Fig. 14: Possible final configuration of the MODARQ - CIDM emergency house.

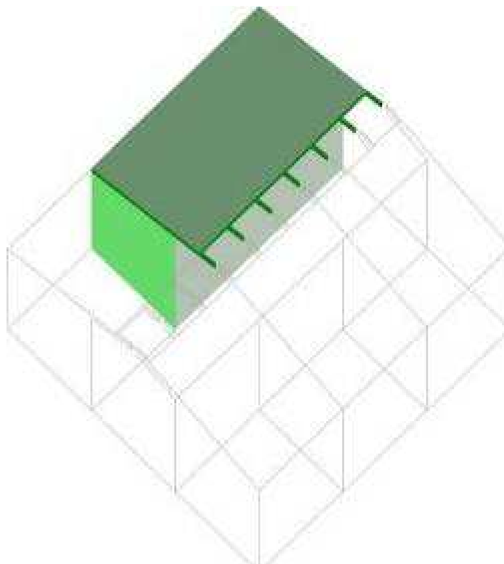


Fig. 15: The figure shows how an initial 18 m2 emergency house could finish as an 81 m2 final solution.

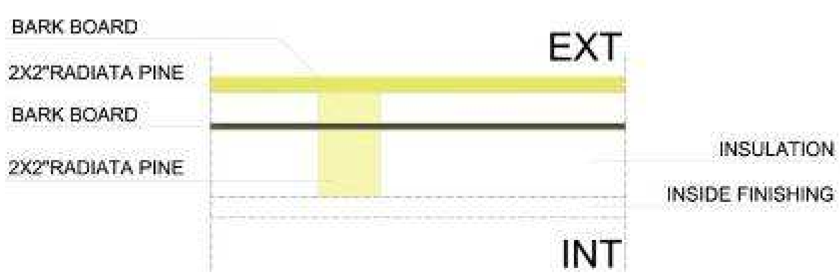


Fig. 16: The figure shows the workings of the progressive envelope.

1.7. The Case of REMA Emergency House

After the 2005 earthquake in the north of Chile, a few local government organizations actively participated in the development of emergency housing.

The role of the local government was to supply the usual emergency house that is provided by the government after natural disasters, but with three design innovations.

First, the local government provided two attached emergency houses per family, doubling the total amount of space from 18 m2 to 36 m2.

Second, the designers modified the angle of one of the two sides of the roof, allowing for more natural light and better ventilation.

And third, they built the wall panels reversed. The families then added bamboo to the outside of the wall structure, and reused the adobe of the destroyed houses as outside finishing and for insulation.

With these innovations, what was initially considered an emergency house could become a final housing solution.

1.8. Conclusions: Mass Housing Production

The ELEMENTAL S.A. social housing project is notable because the design strategy incorporates housing as a tool to overcome poverty.

Also significant is the Modarq - CIDM emergency house, because the design provides flexibility not only for the possible future expansion of the house, but also for the configuration of its envelope.

Coincidentally, in both ELEMENTAL S.A. and Modarq – CIDM houses, the maximum possible additions extend the space up to 75 and 81 m2, which appears more suitable for a permanent social housing solution.

A historical review of the massive social and emergency housing process in Chile, and the case studies, shows that this process is a collective effort between the families, the government and the building technology. However, the case of REMA emergency house confirmed the essential role that the government plays as general coordinator ("fig. 17").

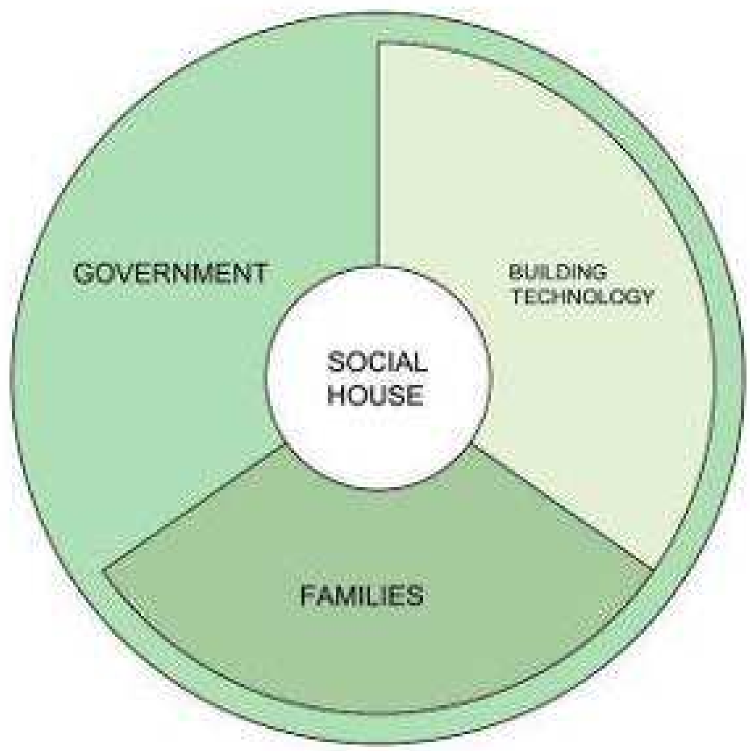


Fig. 17: Relations of success for emergency and social housing solution.

In addition, it is highly feasible that design strategies and building systems could elevate the standards of emergency and social housing solutions, but the success of this depends on housing policies that allow the integration of new housing solutions.

Finally, because of the explosive growth of the urban population, and the enormous number of housing projects developed, the government must contend with the emergency and social housing challenge, not only to house homeless people, but to configure space appropriately within the city (“fig. 18”).

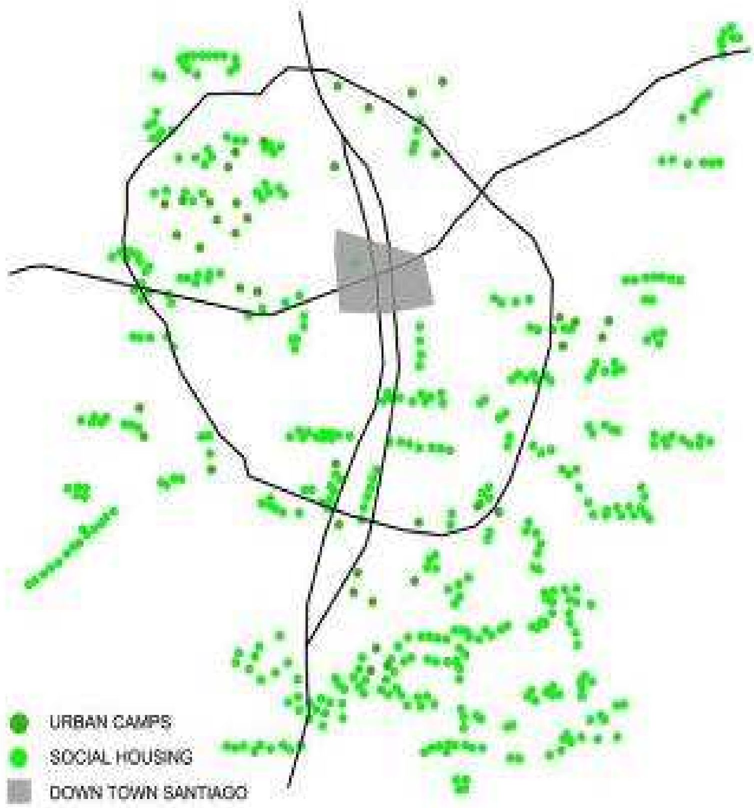


Fig.18. Map of the location of Social Housing projects built in Santiago de Chile, between 1979 and 1994, overlapping a map of the Urban Camps in Santiago de Chile 1979 – 1993.

Note the peripheral location and the city space configuration near the social housing projects and urban camps.

2. A Proposed Space Innovation for Emergency and Social Housing Projects

Following the emergency and social housing process and projects that have been described, one may ascertain targets and challenges for future development (“fig. 19 and 20”).

2.1. Inclusive Homelessness and Flexible Architectural Program.

Projects should incorporate the possibility of developing emergency solutions that may become a final solution. In this way, it would be possible to incorporate everyone into the national housing program and not only those who qualify in the national survey.

Also, projects should have the ability to adapt to changes, such as future additions or interior space re-configuration.

2.2. Environmental Considerations and Specific Context

Currently, the design process of emergency and social housing projects does not consider the environment. The sole aim of the construction companies is to meet the minimal requirements of the building code and minimize costs in order to optimize gains.

For example, in Chile, the house typology is repeated in different climatic zones without considering cultural, social and climatic local characteristics in the design.

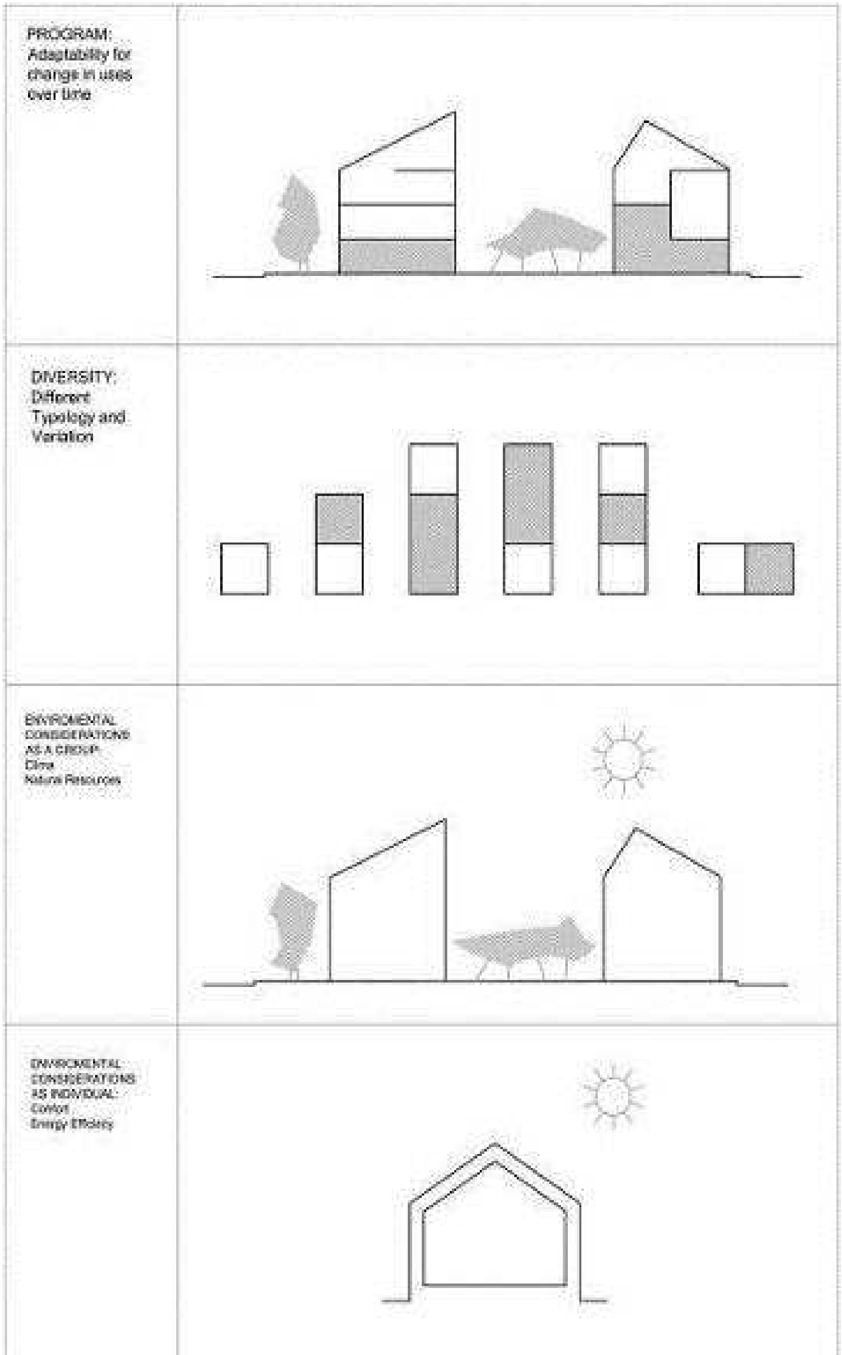


Fig.19: Proposed space innovation for emergency and social housing projects.

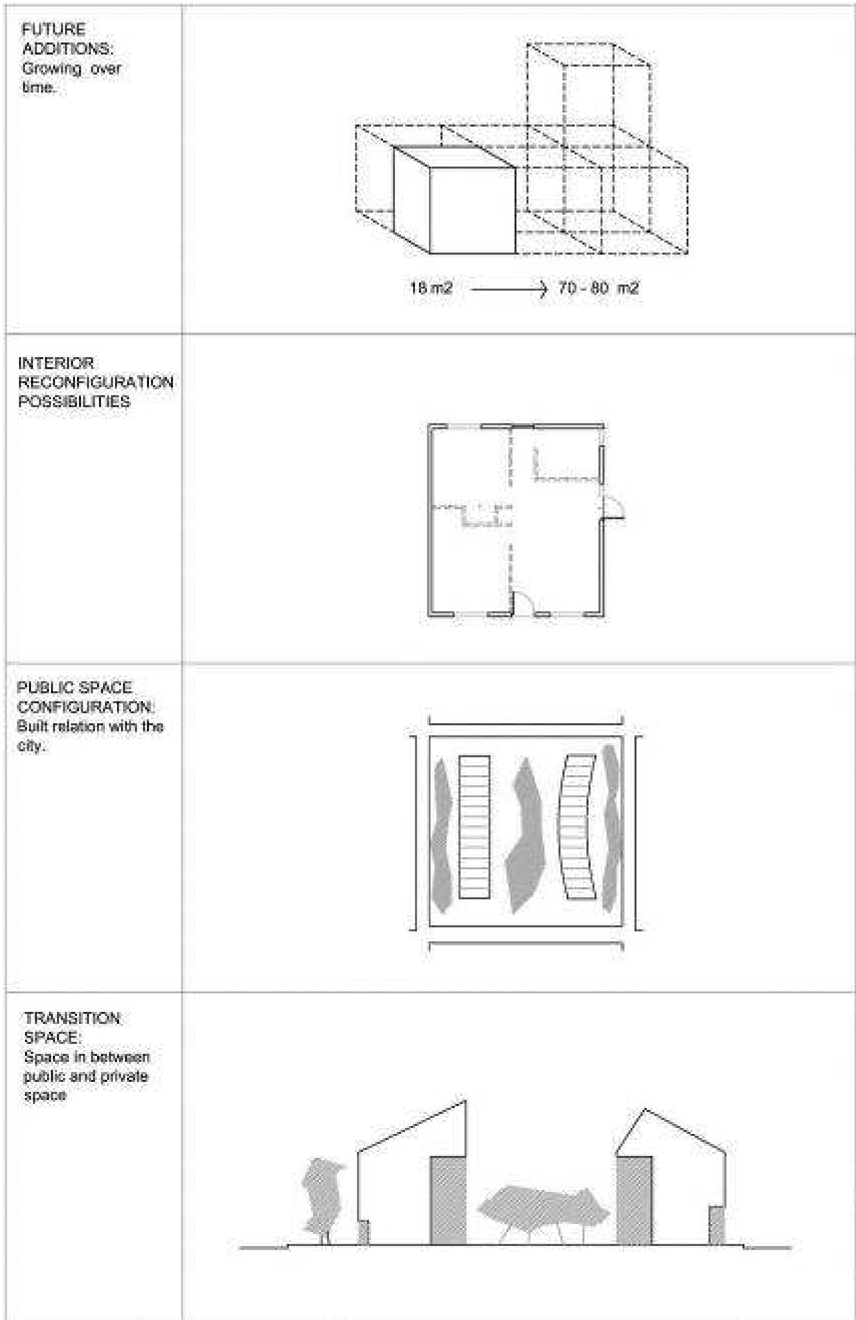


Fig.20: Proposed space innovation for emergency and social housing projects.

2.3. Building Systems

The integration of new building systems could easily elevate the quality standards of emergency and social housing solutions. Also, the new building systems could address possible variations in the chain of production and the changing needs of families over time.

2.4. Density

Currently, most emergency and social housing projects are located in the peripheral areas of the city with several negative externalities.

If projects are located in denser areas, they will provide the families a chance to be closer to their workplaces and social networking opportunities. Also, as the houses are likely to increase in value over time, they also serve as a means to mitigate poverty.

However, as described in the project developed by Elemental S.A., to enable families/companies/government to afford a more desirable location in the city, emergency and social housing projects would have to aim for higher density.

Consequently, the houses would initially be smaller in comparison to the ones that the government commonly provides in suburban areas.

In addition, the projects in an urban context would carry more complexities than the social housing projects developed in the periphery, such as sites with different shapes and space limitations.

2.5. Private, Public and Transition Space Configuration

As part of an urban locale, the social and emergency housing projects play an important role in the configuration of the surrounding public space, but the design of the houses should always consider the need of the inhabitants for privacy.

Therefore, the design of the projects should face a range of programmatic complexity that goes from public to private spaces.

In this programmatic range, a series of spaces or elements in between public and private zones are suitable for the transition.

2.6. Conclusions for Space Innovation in Emergency and Social Housing Projects

In comparison to the projects commonly developed in Chile, the proposed new design considerations for emergency and social housing solutions will challenge architectural projects with their enormous complexity.

To address these new design considerations, several policy initiatives need to be developed. But which material and building technology provides the greatest flexibility in order to overcome this new challenge for mass housing production in Chile?

As a starting point, wood was the chosen material for the innovative prefabricated systems developed in Chile in the early 1960s, and also, the current producers of emergency houses chose wood as a building material.
But, why build with wood today if the innovative prefabricated systems developed have failed and the quality of the emergency houses is low?

3. Wood: A Sustainable Material

There are several reasons to choose wood as a building material for the development of mass housing production.

Currently, there is clear scientific evidence of climate change, due to the greenhouse effect generated by CO2 emissions. These CO2 emissions are directly associated with the energy sector, because the majority of CO2 emissions are produced by the combustion of fossil fuels.

Because of climate change, scientists predict the world's average temperature will rise significantly, melting glaciers, increasing sea levels and rainfall, and among other consequences, causing natural and social disasters in the world (Bustamante 2009).

As one of the highest energy consumers in the world, the construction sector should move towards energy efficiency by targeting low carbon emission buildings. To achieve this goal, the chosen material is crucial, and the carbon emission of wood in comparison to other building materials is low.

Also, the majority of energy production comes from the combustion of fossil fuel, but because these resources are limited, over time their cost will increase.

The variable of embodied energy to produce building material is closely related to the prices of their production, and the embodied energy for wood production is significantly less than for the other building materials commonly used in construction ("fig. 21").

Material	Energy MJ/kg
Concrete	1.11
Bricks (common)	3.0
Concrete block (Medium density 10 N/mm2))	0.67
Aerated block	3.50
Limestone block	0.85
Cement mortar (1:3)	1.33
Steel (general - average recycled content)	20.10
Stainless steel	56.70
Glue laminated timber	12.00
Sawn hardwood	10.40
Cellular glass insulation	27.00
Glass fibre insulation (glass wool)	28.00
Expanded Polystyrene insulation	88.60
Polyurethane insulation (rigid foam)	101.50
Aluminium (general & incl 33% recycled)	155
MDF	11.00
OSB	15.00
Plywood	15.00
Glass	15.00
PVC (general)	77.20

Fig. 21: Material embodied energy production carbon emissions. In green, wood products.

In addition, wood is the only major building material that grows naturally, making it a renewable resource.

Despite the environmental benefits of wood in construction, there are several concerns about its performance quality as a building material. Nevertheless, technological advances in the chain of production of both forest and wood products, allow for great material stability and confidence.

A reflection of the excellent performance of wood as a building material is its frequent use in home construction in developed countries like the U.S. and Canada, and the fact that it is a common chosen material for the most advanced manufacturing research projects in the field of architecture (Schittich 2012).

In Chile, while there is little innovation and development of wood technologies that lead to new architectural solutions for housing, the forest industry, is able to produce high-quality products and has been steadily growing since the mid-1970s (“fig. 22”).

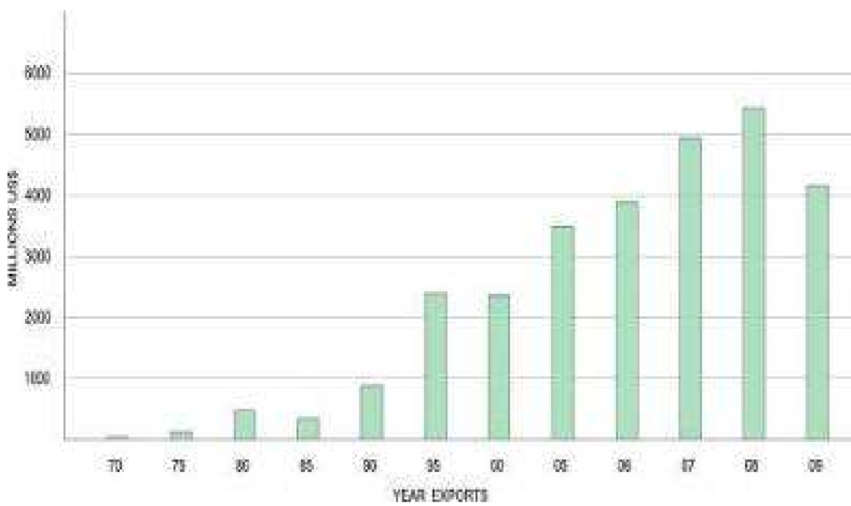


Fig. 22: Chilean wood exports growth.

The environmentally friendly characteristics of wood as a building material and the widespread availability of forestry resources in Chile (“fig. 23”), point to wood as an excellent material with which to confront the homelessness situation in Chile.

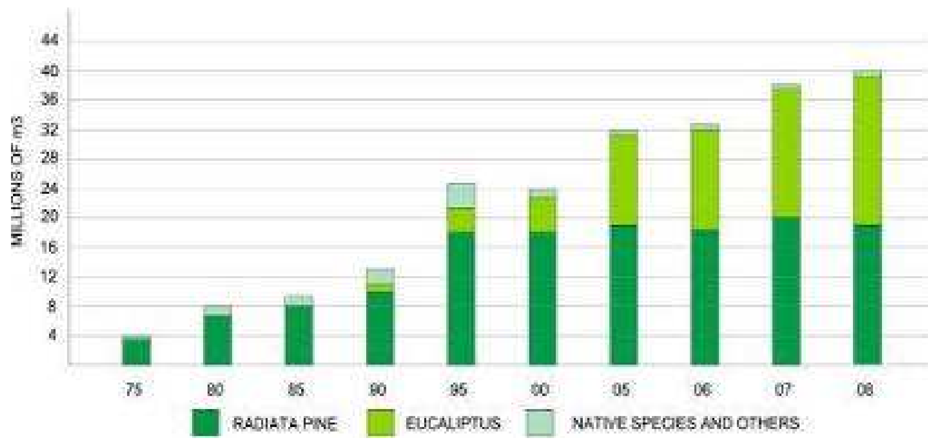


Fig. 23: Chilean Forestry species and production growth.

Chile today enjoys a privileged status due to the production and quality of its lumber, which has become the nation's second-most exported natural resource after minerals (Gonzalez 2010).

Given the technologies and construction of wood in Chile, and considering its excellent properties from the environmental point of view, the lack of development in wooden housing construction over the last forty years is disappointing. . This lackluster progress is especially striking considering the continuous expansion of housing construction over the same period of time, and the tradition of wooden building characteristic of the country throughout its history.

The developers have detected, through several studies, that the limited use of wood is because of the problems of security and durability that wood presents, and a strong cultural stigma that associates wooden construction with an emergency housing solution, or with second housing.

Also, the wood labour tradition is primarily related to the Chilean native forest, most of which is classified as hardwood species. Today, these native species are protected by law and the mass industry of wood production as a building material is based on radiata pine, which grows very fast, and is classified as a softwood species.

3.2. Radiata Pine: A Softwood Species in Architecture

Classified as softwood, and in comparison to hardwood species, the mechanical properties of the Chilean radiata pine are low, and its response to changes in climatic conditions like humidity and temperature is unstable. Because of these qualities, building houses with radiata pine requires special focus on the certification of the material, the design of the project and the manufacturing process.

Significant advances have been made in the control and certification of the raw material, but recent studies have found that about 50% of the radiata pine sold on the national market falls short of the optimal conditions for construction. This means that good quality products are exported and the material that is left over stays in Chile.

Nevertheless, through a model of a continuous certification throughout the chain of production of wood houses, current research in Chile attempts to encourage the use of wood in massive economic housing. In this piece of research, improvements in the design of the envelope of the houses, in a platform frame system, have yielded excellent architectural and full-scale scientific testing results.

In order for the design improvements to satisfy the minimum requirements of habitability and durability, the construction of wooden homes requires skilled labour and experience, but the old wood tradition remains. Also, these improvements in design and the certification processes in the chain of production for wood houses, raises their cost, making them uncompetitive against houses built out of other materials. However, and particularly because of its cellular microstructure, softwood performs better than hardwood in the development of wood-based products made out of particles or fibres, such as paper, cardboard and particle boards, among others.

3.3. Wood-Based Products as a Building Material

Wood-based products are a new branch of the wood building construction industry. In comparison to traditional wood products, wood-based products have the significant advantage of being made from wood working waste or low-value tree species.
Wood-based products are primarily composed of particles and adhesives. To create these products, particles are oriented in terms of structural behavior and mixed with adhesives, and in most cases with large amounts of water. Then, at high temperatures, the mixture is pressed or extruded through plates, rollers or molds, allowing the glue to stick to the particles.

The adhesive, which constitutes a low percentage of the composite, nonetheless plays a fundamental role in the final product.
From these processes, it is possible to obtain a range of different products for construction.

These products have different characteristics that befit a range of functions, from structural elements to insulation elements. As an example, the Oriented Strand Board (OSB) is the most popular structural board in the world market. Also, the medium-density panels, which are widely used for making furniture, and the recently developed oriented strand lumber and the parallel strand lumber which are used for structure. The oriented-strand lumber and parallel-strand lumber are cured in a microwave process. Both of them have high structural capacity, provide excellent material stability and are suitable for large spans.

With respect to wood-based construction products, Chile has a long tradition of manufacturing and exporting particle and fibre boards for furniture, but this is not so in the case of structural elements. For example, the first OSB industry was installed in the year 2000. In addition, there are no industries that produce oriented-strand lumber and parallel-strand lumber in Chile.

However, in wood fibre products, Chile is internationally recognized for the quality and manufacturing of its pulp and paper (5.000.000 ton/year). This production constitutes more than 40% of the forestry production of the country, but pulp and paper are generally not considered building materials ("fig. 24").

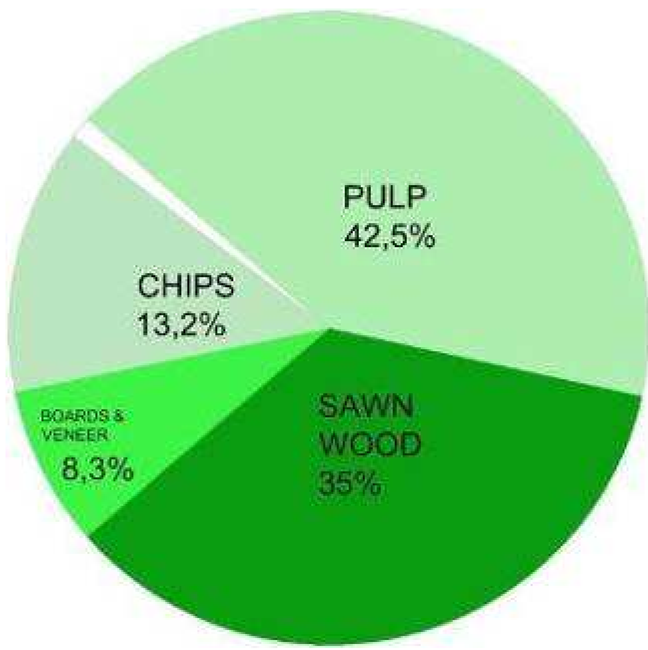


Fig. 24: Chilean Forestry Products. Note that the 42.5% is Pulp, which is not considered a building material.

But should pulp and paper be overlooked as building materials?

Traditional Japanese architecture reminds us that the use of paper as a building material is not new; in Japan, paper products are used as coverings in light-framed wood panels, such as sliding doors or interior wall dividers.

And notably, recently developed projects, with strict laboratory tests, have used paper as a structural element with excellent architectural results, and as an alternative and inexpensive solution for emergency housing projects.

Also, recycled paper, because of its environmentally innocuous characteristics in comparison to other materials commonly used in construction, has become quite popular as insulation.

In addition, and as described before, one of the reasons for the late response of the Chilean government to provide emergency houses in the 2010 earthquake, was because the country ran out of construction materials, and under urgent circumstances, homeless and displaced people were open to build with alternative solutions.

3.4. Pulp and Paper Process

Today, the fact that structures are built with paper products does not necessarily mean that they must be temporary; if proper films and treatments are applied to the material during the production process, the buildings can resist fire and humidity according to building codes requirements.

For paper-making, in a process called pulping, the first step is to separate the lignin and other materials from the cellulose. There are two primary ways of making pulp: The mechanical method and the chemical method, each presenting advantages and disadvantages.Mechanical pulping is based on finely grinding or chopping the wood to separate the cellulose fibers from everything else. It is very efficient, converting 90% or more of the wood into pulp.

However, the resulting pulp contains most of the lignin it started with, causing the resultant paper to turn yellow or brown when exposed to the sun. The process also tends to produce fibers that are short and stiff, giving a poor-yield paper that isn't very strong. For that reason, mechanical pulps are mainly used for packaging, newsprint, and other applications that require minimal sturdiness.

Chemical pulping uses chemicals, heat, and pressure to dissolve the lignin in the wood, freeing the cellulose fibers. In the process, the wood and chemicals are cooked in digesters to remove lignin among other components. In the chemical pulping process, it is possible to obtain longer and stronger fibres than in the mechanical pulping method.
To make the paper, the pulp is highly diluted with water, and the mixture is sprayed in layers to make a mat on a moving mesh screen.

Finally, the mat goes through several vacuum processes to de-water, compact, and dry.

3.5. Conclusions: Wood as a sustainable material

As described, all wood-based products run through similar production methods (“fig. 25”). During their production it is possible to incorporate additives that will increase their performance against external agents, such as termites and humidity.

Fig. 25: Wood based product material relationships.

The excellent performance of softwood species in the development of wood products with great durability and stability for construction points to a potential market for Chilean radiata pine products.

Also, the architectural examples shown, and the cost comparison between the emergency and social housing solutions described, present pulp and paper as a real alternative building material ("fig. 26").

	SOCIAL HOUSE IN CHILE	ELEMENTAL S.A SOCIAL HOUSE	EL HOGAR DE CRISTO EMERGENCY HOUSE	MODARQ EMERGENCY HOUSE	PAPER EMERGENCY HOUSE IN KOBE, JAPAN
m2	40	25	18	18	52
Cost U$	17,000	17,000	865	3000	2000
Cost U$/ m2	425	680	48	167	38
Additions m2	12	50	-	63	-
Total m2	52	75	18	81	52

Fig. 26: Social and emergency houses cost comparison.

But, how can we integrate wood-based products into mass housing production?

What difference would wood-based products make in the mass housing production process?

Today, the digital era is forging a different architecture, providing unprecedented opportunities for a significant redefinition of the production of buildings.

4. Digital Fabrication

Integrating manufacturing and assembly into the design process, architects, engineers and builders have an opportunity to redefine the relationship between architecture and production (“fig. 27”).

This redefinition is about strong communication between all the parts involved in the building process, and today, computer software, such as computer-aided design (CAD) and computer-aided manufacturing (CAM), allows this communication to happen.

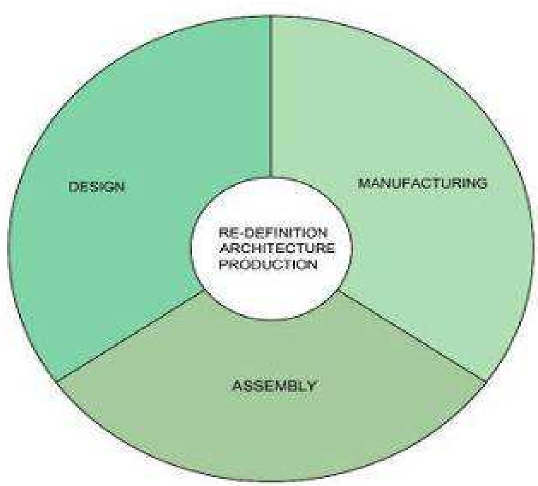


Fig. 27: Re-definition architecture production.

For example, these design software applications now are able to incorporate more sophisticated solid and surface-design modeling with a structural analysis of the architectural components.

Also, the digital designs can be directly translated into tangible three-dimensional forms using Computer Numerically Controlled (CNC) fabrication tools. These CNC fabrication tools are capable of manufacturing building components with high speed and great precision.

New software and machines are creating new opportunities by simplifying the production and construction of very complex forms, which until recently, were difficult and expensive to produce and assemble using traditional construction technologies.

In this new digital and manufacturing context, increasing importance has been given to the role of parametric design. This parametric design is easily applicable to the new design and manufacturing software, and is based on the consistent relationship between the elements in the design object.

This consistent relationship between the elements allows changes in single elements to propagate through the whole system (Ferré and Sakamoto 2008).

Therefore, when using a parametric software system in the design and the building process, changes are fast and easy to manage, providing great flexibility in the production line.

Digital fabrication has been divided into two main areas, Subtractive Fabrication and Additive Fabrication (Kolarevic 2003) .

Subtractive Fabrication is the manufacture of products by numerical control machine tools that reduce a solid block of metal, wood or other material by any combination of drilling, cutting and sanding.

Additive Fabrication involves forming structures incrementally by adding materials layer-by-layer. This technique is called Stereo-lithography. Stereo-lithography is defined as a method for making solid objects by printing thin layers of a curable material one on top of the other. The most popular tools for this kind of fabrication are 3D printers.

3D printing is a promising technology for many reasons, including the high quality of the fabricated components, the great possibilities for manufacturing very complex geometries and the ability to customize according to specific requirements.

While most 3D printing processes are limited to model-size structures, current research projects explore the potential of 3D printing for full-scale applications.

This research will focus on Additive Fabrication, because of the commonalities that the production process has with that of products made out of wood particles, such as layer-by-layer forming, the fundamental role of the adhesive and the curing stage.

4.1. State of the Art

Recent research projects have built full-scale printers capable of extruding materials in layers with different types of printing methods and curing processes.

Three of these projects are notable in the context of this research. Contour Craft (CC) of the University of Southern California, and

Concrete Printing (CP) from Loughborough University extrude a special type of concrete from a nozzle that follows the shape of the 3D element previously designed on a software application.

On the other hand, D-shape from Dini Engineers following the same principles of the traditional 3D printers, scales the machine up to 6 x 6 x 8 meters.

4.2. University of Southern California: Contour Craft

CC was first developed in 1990 and has published more than 7 patents (Khosnevis 2009a; Khosnevis 2009b; Khosnevis 2010a; Khosnevis 2010b; Khosnevis 2010c; Khosnevis 2010d; Khosnevis 2011). It operates in a fashion similar to a CNC machine, but instead of cutting material, it extrudes concrete in layers through a nozzle.

The material runs through two processes: one of extrusion, in which the material flows through a screw, and the other, of curing, in which the material solidifies.

Curing starts when the extrusion begins and the shapes of the objects are controlled by a side and top trowel (“fig. 28”).

The target of the project is to considerably reduce the time of construction through a full-scale 3D printing system that is taken to the construction site. (“fig. 29”).

Innovation in the design of the walls to improve the structural performance has yielded good structural results (“fig. 30”), but the tension strength performance is still unsatisfactory to permit CC to be considered as a possible building method. Therefore, the system needs to be reinforced.

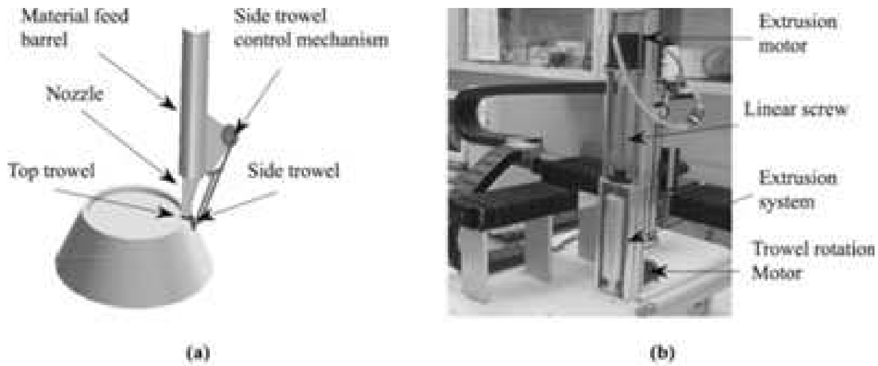


Fig. 28: Shape control by a side and top trowel. Linear extrusion system.

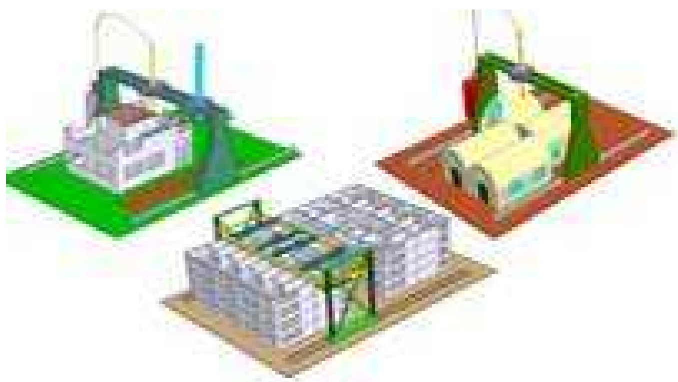


Fig. 29: Onsite project.

Fig. 30: Extruded layers of 1cm height. Design wall with structural improvements.

4.3. Loughborough University: Concrete Printing

Concrete printing is a process performed by a full-scale 3D printer that extrudes a special type of concrete in layers.

The shape of the elements is controlled by the size of the nozzle and the extrusion of very thin layers.

The general target of the research is to build prefabricated pieces in the industry and then assemble them on site, bringing speed and quality control to the building process (Buswell et al. 2007) .

Looking for more flexible design possibilities, the research team includes architects and designers. Although the elements built have an attractive design, they present problems under tension strength, and they are too heavy for easy transportation.

4.4. Dini Engineers: D – Shape

With two published patents (Dini 2008), this method is an inkjet printing system similar to a regular-size 3D printer but upscaled to 6 x 6 x 8 meters.

The printer creates the model one layer at a time by spreading first a layer of powder, in this case sandstone, and then inkjet printing a binder over the layer of powder, creating a cross-section of the part. The process is repeated until every layer is printed.

The shape control depends on the printing resolution, in this case 5 dots per inch (dpi), and its target is to work under a prefabricated system, building the elements in the industry, and then assembling them on site.

The developers of the technology have already collaborated with architectural firms and artists, and the flexibility that the system allows is shown in its greatly interesting results.

One of the problems of this project is that after 3D printing, the elements need a lot of sanding for finishing; also, the prefabricated printed elements are too heavy for easy transport. In addition, the tensile strength resistance is still too low for the prefabricated elements to be considered suitable building materials.

4.5. Others

3D printing technology has multiple applications. Research about 3D printing for medical supplies has yielded interesting approaches to possible architectural applications.

Despite the difference in scale for this research, special attention is given to the precision of the material deposition through different types of nozzles, and for structure, the possibility of mat forming with hollows for material optimization.

4.6. Conclusions: Full Scale 3D Printing

Although the three pieces of full-scale 3D printing research presented succeed as a first approach for architectural application, the material composition failed under structural requirements as an architectural element.

Also, as a prefabricated system, the weight of the architectural elements makes them difficult to handle, especially for transportation and assembly. In addition, the build-on-site process requires a lot of accuracy on the construction field, but at the moment, this accuracy is not possible to guarantee.

While the three pieces of research described try to 3D print interesting and complex architectural elements, their goal is only to meet the structural requirements. None of them approaches the question of the kind of architectural performance that 3D printed elements should have.

Considering the similarities in the processes of 3D printing and manufacturing of wood-based products, the positive structural performance of wood-based products, and their low weight in comparison to the other commonly used building materials, calls attention to the fact that no one has tried to 3D print wood.

This research proposes, under a prefabricated method, full-scale 3D printing of a wood-based material as a tool to combat homelessness, and space innovation in social and emergency housing projects.

The available material in Chile and its excellent environmental performance in comparison to other building materials, in addition to the positive mechanical properties of wood-based products and the enormously flexible design possibilities and speed of the 3D printing construction system, make this a good prospect.

But, how can we 3D-print a wood-based material that meets the structural requirements for housing?
What kind of architectural performance should the 3D-printed elements exhibit to be considered appropriate building elements for housing?

First, as described, the success of the structural wood-based products is subject to the adhesive and orientation of the wood fibres.
Second, the architectural performance of the building system should provide an acceptable level of habitability and durability.

5. The Grain Direction of Wood-Based Products and the Architectural Performance of a House

One important difference between wood and the other materials commonly used in construction is that it is an anisotropic material.

Anisotropy is the property of being directionally dependent, as opposed to isotropy, which implies identical properties in all directions. This difference in wood can be measured with the structural results of the material along the different axes of the elements.

On the other hand, a good architectural project must meet certain requirements of habitability and durability. These requirements not only apply to the structural performance of the project, but also to its ability to provide an appropriate level of comfort.

To provide an appropriate level of comfort, the envelope plays a fundamental part as equalizer of the physical differences between the internal and external environments to which the house is submitted.

The design and material composition of the envelope can also be optimized according to climate, programmatic use, and the specific architectural requirements of the project.

5.1. The Finite Element Method (FEM)

A few decades ago, the computer-based Finite Element Method (FEM) of structural analysis was born. In the FEM environment, the structurally analyzed component is broken down into finite geometric sections. In their totality they describe the shape of the component.

Also in FEM, it is possible to assign material, mechanical and connective properties to the object. Furthermore, it is possible to apply specific loading cases to the element, from which the results of displacement, stresses and strains are obtained with great accuracy and speed.

This accuracy finally entails an optimization of the element which is going to be built, and thus an efficient use of material. In addition, one of the major contributions of FEM is that very complex shapes can be easily analyzed (“fig. 31”).

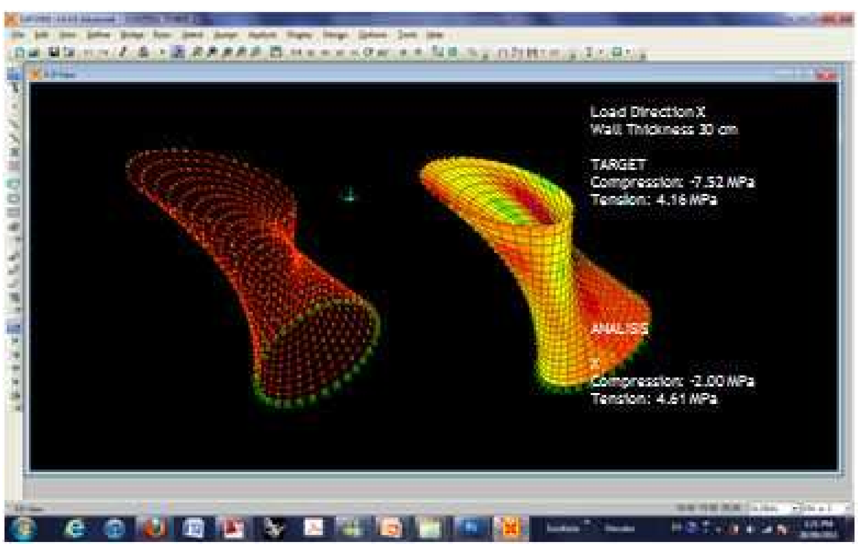


Fig. 31: Software environment. Structural Analysis Program (SAP2000). Picture from Structural Analysis and Digital Program Course. SALA-UBC.

Following the FEM principles, the Karlsruhe Research Centre led by Prof. Claus Mattheck, through a study of physical structures in nature, has developed three complementary pieces of software for the shape optimization of the analyzed elements.

The Self Kill Option (SKO) software proposes adjustments to the elements by eliminating material. The software eliminates the parts of the elements that are under low stress; and thus the final shape responds exclusively to the stresses to which it is submitted.

The Computer-Aided Optimization (CAO) software improves the structural performance of the elements by increasing their size. The variable of temperature is incorporated into the element— where there is more stress, there is a higher temperature and where there is less stress there is a lower temperature — therefore, CAO proposes modifications to the element with possible expansions of the parts exposed to high stress.

Throughout his studies, Professor Mattheck incorporated methodologies designed to emulate structures found in nature into the SKO and CAO software. The simulations defined the optimal shape of elements, according to their material composition and loads to which they would be submitted, but based on materials with homogeneous elastic behavior (isotropic).

In the same Research Centre, examinations of the direction of the structural forces in the elements studied, reveal a strong similarity with the course of the grain in the trees. Therefore, for calculations with wood materials (anisotropic) it is possible to assign grain distribution to the force flow, and assume a much higher modulus of elasticity in the direction of the force flow than transversely to it.

With these principles Computer Aided Internal Optimization (CAIO) software was developed, and the structural simulations and laboratory tests have shown quite significant decreases in the shear stresses in the elements with optimized design arrangement of its fibres.

In the words of Prof. Claus Mattheck and following his studies about nature, with CAIO: "... we can imitate the internal architecture of the tree, namely its optimum grain direction. It is conceivable that this too will be used in the optimization on technical composite material made of fibres".

Also, for future development "...the manufacturing possibilities for optimum "weaving" of fibre composite in accordance to previously optimized distribution are not yet well developed..., however, we should not lose sight of this goal for fibre composites. With these a true ecodesign would mean not only optimization of the external shape but also of the internal fibre distribution. What could emerge is "technical wood" with the possibility of artful connections finding their highest degree of perfection" (Mattheck 1998).

5.2. The Core of the Envelope

Today many of the scientific studies related to housing in architecture focus on the behavior of the envelope.

In housing, the envelope is constantly mediating between the internal and external climates, so its quality is directly related to the level of comfort and durability of the house (“fig. 32”).

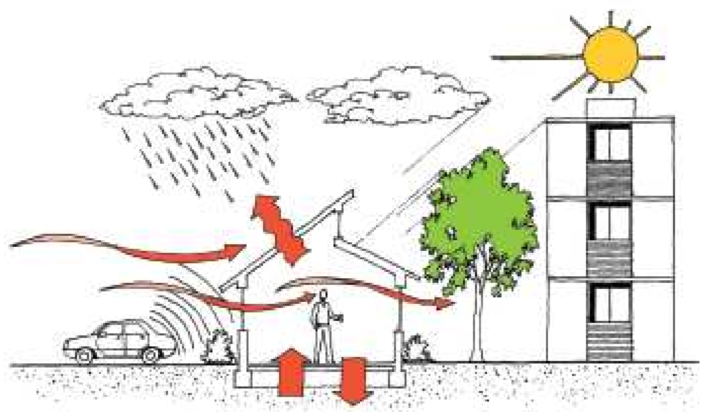


Fig. 32: Envelope quality is directly related to the level of comfort that the house provides.

To attain an adequate comfort target, the envelope is composed of various elements. Each element responds to different requirements, and an appropriate response of the elements depends on their material characteristics and their specific location in the envelope.

In addition, the nature of the construction material and its location in the envelope vary according to the material’s purpose, because the requirements of the parts, such as walls, roofs or floors, are different (“fig. 33”).

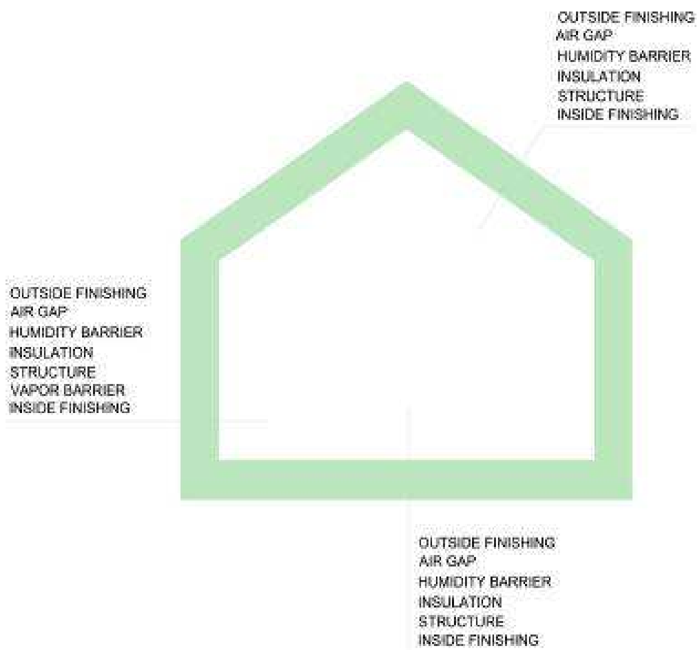


Fig. 33: Environmental requirements of the envelope vary according to its specific location.

An agreement of international cooperation between the University of British Columbia and the Timber Research and Development (CIDM) of the Catholic University of Chile, outlines what became one of the most important pieces of scientific research for wood housing in Chile.

In the year 2004, the CIDM organized the first International Symposium for Wood Houses in Chile.
Experts from leading wood-manufacturing countries and from all disciplines involved in the construction of wood houses, met together in Chile with the aim of providing two things: First, an overview of the state-of-the-art in research, innovation and development of wood houses around the world.

Second, a design, under a platform frame building system, of the envelope characteristics for economic wood houses in three different climatic zones in Chile (“fig. 34”).

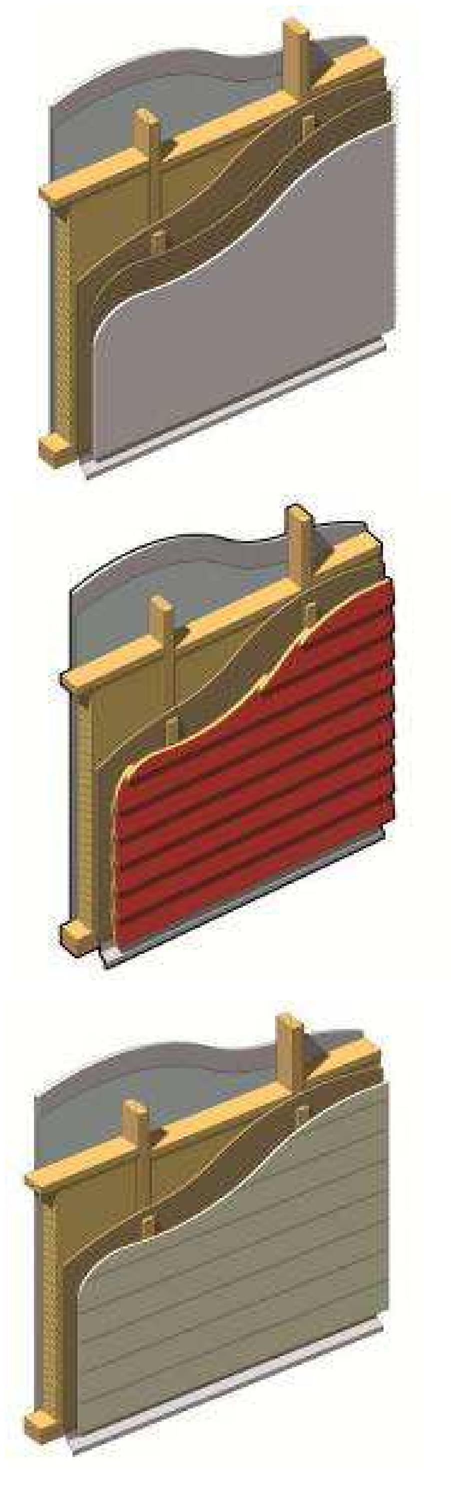


Fig. 34: Chilean wooden envelope for wood housing. International Simposium 2004.

The final design developed at the symposium has yielded excellent scientific results under software simulations, laboratory tests of structure and resistance to fire and humidity, and full-scale architectural prototypes.

During the symposium, it should be noted that although greater thickness in the walls was proposed to increase the amount of thermal insulation, the final wall proposal was restricted by the national social and economic reality, to 90 mm between the studs of the platform system.

Also, the structural test results showed that there was an enormous structural capacity in the proposed system, suggesting that the system could even work well for a 3- to 4-storey building.

From this, it is possible to conclude that despite the excellent results in the proposed system, there is an inconsistency between the thermal resistance required and the proposed structure.

In addition, an analysis along the thickness of the envelope, revealed wood elements with different densities and function, but aside from differences in exterior finishing, the envelope would have the same specifications for the three different climatic zones in the country the analysts studied (“fig. 35”).

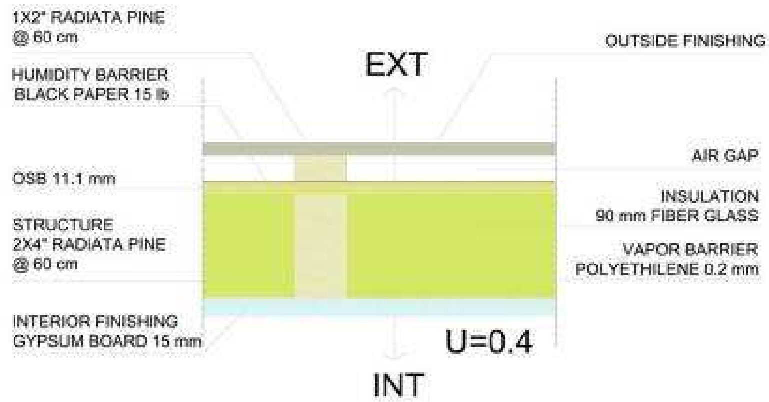


Fig. 35: Chilean wood envelope for housing. International Symposium 2004.

5.3. Conclusion of the Grain Direction in Wood-Based Products and the Architectural Performance of a House

As described, and despite the enormous progress made by the International Symposium to design a Chilean envelope for wood housing projects, the proposed envelope solution is still not perfectly appropriate for all environments, and there remains a need to optimize resources for emergency and social housing solutions in order to improve their architectural quality and construction.

The direction of the fibres in structural wood-based products that exists in the market today, corresponds to mass production of a particular construction element, but Prof. Mattheck's research indicates the possibility of making advancements toward a wood based product that optimally responds to an infinite range of structural requirements.

This possibility would result in great diversity and flexibility in design and production, but as defined, the optimization of architectural elements should not only seek to improve the strength/integrity/performance of the structure, but also its capacity to provide comfort.

How can we incorporate structural and envelope optimization into the manufacture of an infinite rage of particular architectural elements?

6. A Proposed Relation for the Manufacturing of Optimized Wood Architectural Elements

First, 3D printing works under a technique called Stereo-lithography. Stereo-lithography is a building method for making solid objects by printing thin layers of a curable material, one on top of another. This building system is very flexible because it is able to build an infinite range of elements with great complexity, accuracy and speed.

Second, the principle for the structural analysis of an architectural element is based on the mechanical properties of the material, the loads it will bear, and the area section of the architectural element ("fig. 36").

$$\Delta = \frac{P}{A}$$

Δ = Max. Strees
P = Load
A = Area

Fig. 36: Structural formula.

Usually, the material´s mechanical properties and the loads it will bear are known; however, the area of the elements initially proposed by the architect, is submitted to the engineers' structural analysis, and may vary according to the structural optimization.

And third, an appropriate level of habitability and durability of an architectural project is strongly related to the level of comfort it provides. Here, the performance of the envelope plays the fundamental role of equalizer between the external and internal environments.

To achieve an appropriate level of comfort, the thermal resistance of the envelope is crucial, and this thermal resistance is related to the specific thermal conductivity properties and thickness of each element that composes the envelope ("fig. 37").

$$U = \frac{1}{Rsi + \sum \frac{e_1}{\lambda_1} + Rse} \quad \frac{W}{m^2\,°C}$$

Rsi = Interior Surface Resistance
e = Thickness
λ = Material Thermal Conductivity
Rsi = Exterior Surface Resistance

Fig. 37: Thermal resistance formula.

In general, the thermal conductivity of the building materials is known, and the thickness of the elements may vary according to the specific thermal resistance target of the architectural project.

As described, the sectional optimization of the architectural elements may vary according to the structural and thermal resistance requirements, and the 3D printing building system works by printing sections of the given elements.

For these coinciding principles, this research proposes a relationship between structure, thermal resistance and additive fabrication in the section of the architectural elements (“fig. 38”).

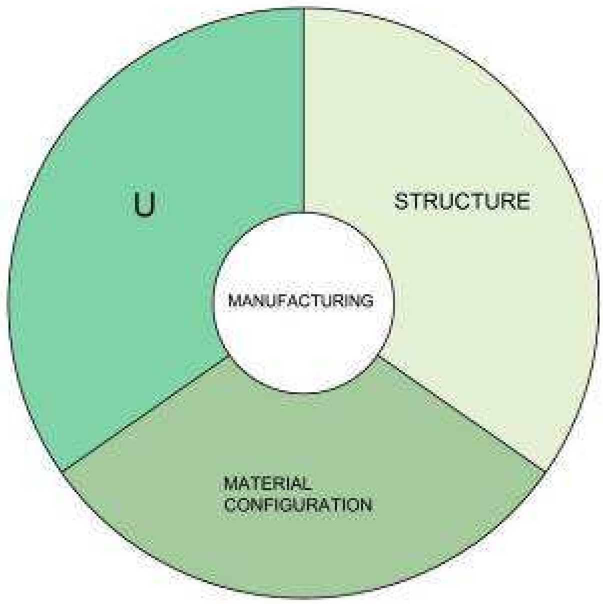


Fig. 38: Relation in sections.

But, for the possibility of building an infinite range of architectural elements, different structural performance and thermal resistance factors will be required; this means that, for the maximum optimization, a different material configuration in the section of the architectural element will be needed.

Because of this situation, a manufacturing relationship between thermal resistance, structure and material configuration is proposed (“fig. 39”).

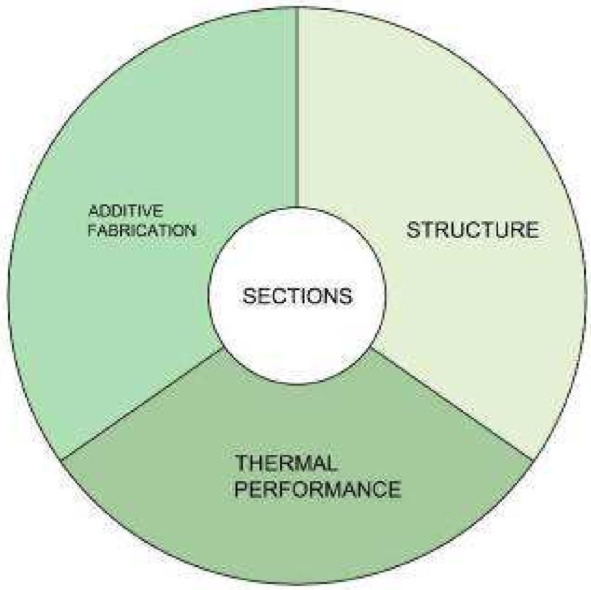


Fig. 39: Manufacturing Relation of New Wood Based Material.

But, which material could meet an infinite range of structural and thermal resistance requirements?

As described, wood-based products can be used for a range of different possible components, each one with different characteristics and properties, such us structure, insulation, or finishing.

With FEM and the complementary software developed by Prof. Mattheck, we know that it is possible to structurally optimize wood fibre products.

But, if we are able to assign, in a FEM environment, different wood-fibre materials to each finite element, we could also optimize the performance of the architectural elements with an iteration method between structural and thermal requirements with the material configuration (“fig. 40”).

But how?

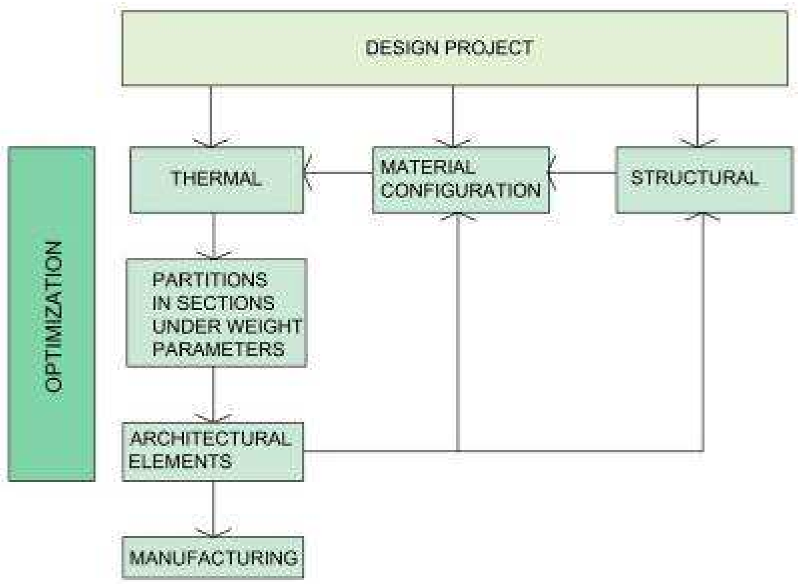


Fig. 40: Iteration method for optimization.

7. Material Optimization: Software Simulations and Methodology

With a proposed manufacturing relation between wood-fibre material configuration, structure and thermal performance, this chapter describes a possible approach to material optimization for prefabricated full-scale wood-based 3D printed architectural elements through an iteration method.

Also, it should be noted that the possible approach for material optimization is made with the structural simulation software SAP 2000; this means that the structural results are reliable, but the thermal performance of the analyzed object is assumed to be correct by its material conductivity.

7.1. Constitution of the Architectural Element and the Bending Principle

To begin, a very simple architectural element is analyzed in terms of structural and thermal performance.

The chosen architectural element will be a prefabricated part of a roof. As a part of a roof, the prefabricated architectural element would need to meet the challenge of spanning a space. It would also contribute substantially to the thermal performance of the house, as the majority of heat transfer typically occurs through the roof.

The prefabricated simulated roof will be 300 cm long, as this is a common measure in emergency and social housing projects in Chile, and 60 cm in width, to make the prefabricated piece easy to handle for construction.

First, it is necessary for the simulations to incorporate the same mechanical properties and degree of thermal conductivity as the materials that will be used in the architectural element: in this case, radiata pine and recycled paper (“fig. 41”).

Second, it is necessary to state the thermal performance target; in this case, U=0.3 is proposed, because this value will cover the thermal requirements of five different climatic zones of Chile.

General knowledge in construction and structure suggests radiata pine has better structural capacities than paper, so a good way to start is to measure the thickness of the architectural element as if it were made only of a solid piece of radiata pine.

In order to meet the thermal resistance target (U=0.3) and according to the thermal conductivity of radiata pine, the thickness of the element should be 30 cm.

At the moment we have a solid prefabricated radiata pine roof element of 300 x 60 x 30 cm. (“Fig. 42”) that meets the U value requirements of the Chilean Building Code, but also, as a prefabricated part of a roof, this simulation is used to analyze the bending behavior of the architectural element.

The bending principle is characterized by the behavior of a structural element subjected to an external load applied perpendicular to the longitudinal axis of the element.

When loads are applied, the element presents on its upper side, stresses of compression, and on its lower side, stresses of tension. The space in between compression and tension exhibits “0” stress (“Fig. 43”).

	Density (Kg/m3)	Thermal Conductivity (W/m°C)	Modulus of Elasticity (KPa)	Yield Strength (KPa)
Radiata Pine	450	0,043	10,000,000	40,000
Recycled Paper	37	0,05	300	

Fig. 41: Physical characteristics of radiata pine and recycled paper.

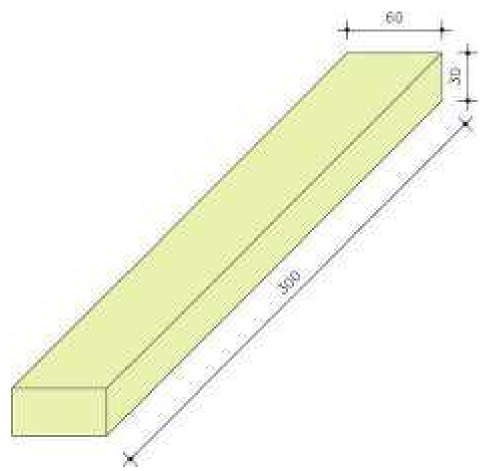


Fig. 42: Architectural element.

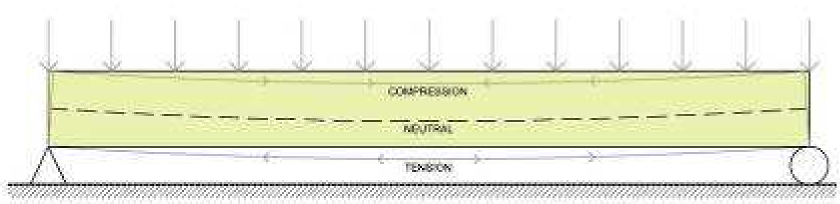


Fig. 43: Tension and compression forces under bending.

7.2. Steps of Simulation

To prove the possible material optimization of the solid piece of 300 x 60 x 30 cm radiata pine, first we entered the mechanical properties of radiata pine into the structural software, then we assigned the necessary joints restrains, and finally we applied a surface pressure load of 2.5 KN/m2 to the top.

The stresses are shown to be consistent with the bending principle. Also, the results in comparison with the yield strength properties of radiata pine show an over structure of the architectural element ("fig. 44").

As described, in the FEM environment, it is possible to divide the elements into finite sections. The totality of these sections will describe the shape of the element, but in this case, instead of analyzing the architectural element as a solid, we are going to analyze it as a shell structure.

But, why?

In a FEM environment, shell structures are analyzed in finite area elements. The totality of the area elements will describe the shape of the analyzed element. To these area elements, it is possible to assign layers with different thicknesses and material configurations.

Three layers of 300 x 60 x 10 cm of solid radiata pine, one on top of the other, will configure the shape of the element.

1

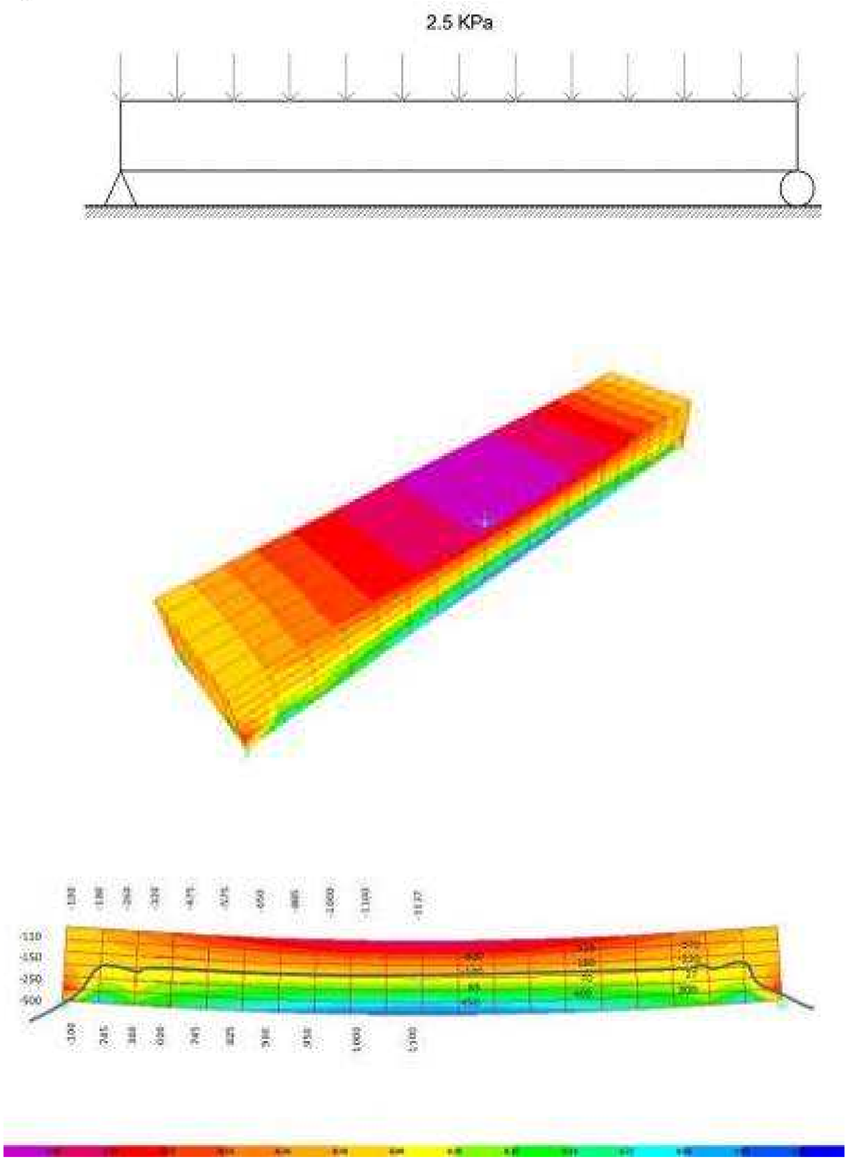


Fig. 44: Simulation 1.

The same joint restraints and loads from the previous structural simulations are applied to the object, and the results show that it is possible to analyze a wood architectural element as a shell structure ("fig. 45").

The third and final stage is the search for material optimization. The architectural element is divided into several finite-area elements. Thus, instead of having one material with one type of layer configuration, we would have two materials with three different types of layer configuration.

The design optimization would follow the stresses shown in the first and second stage. The layer configuration with less structural capacity is assigned to the areas subject to fewer stresses, and the layer configuration with stronger structural capacities is assigned to the areas with greater stresses.

The results show that material optimization is possible, but to improve the architectural element, the optimization should work with software that incorporates structural and thermal requirements into the proposed iteration method for manufacturing ("fig. 46").

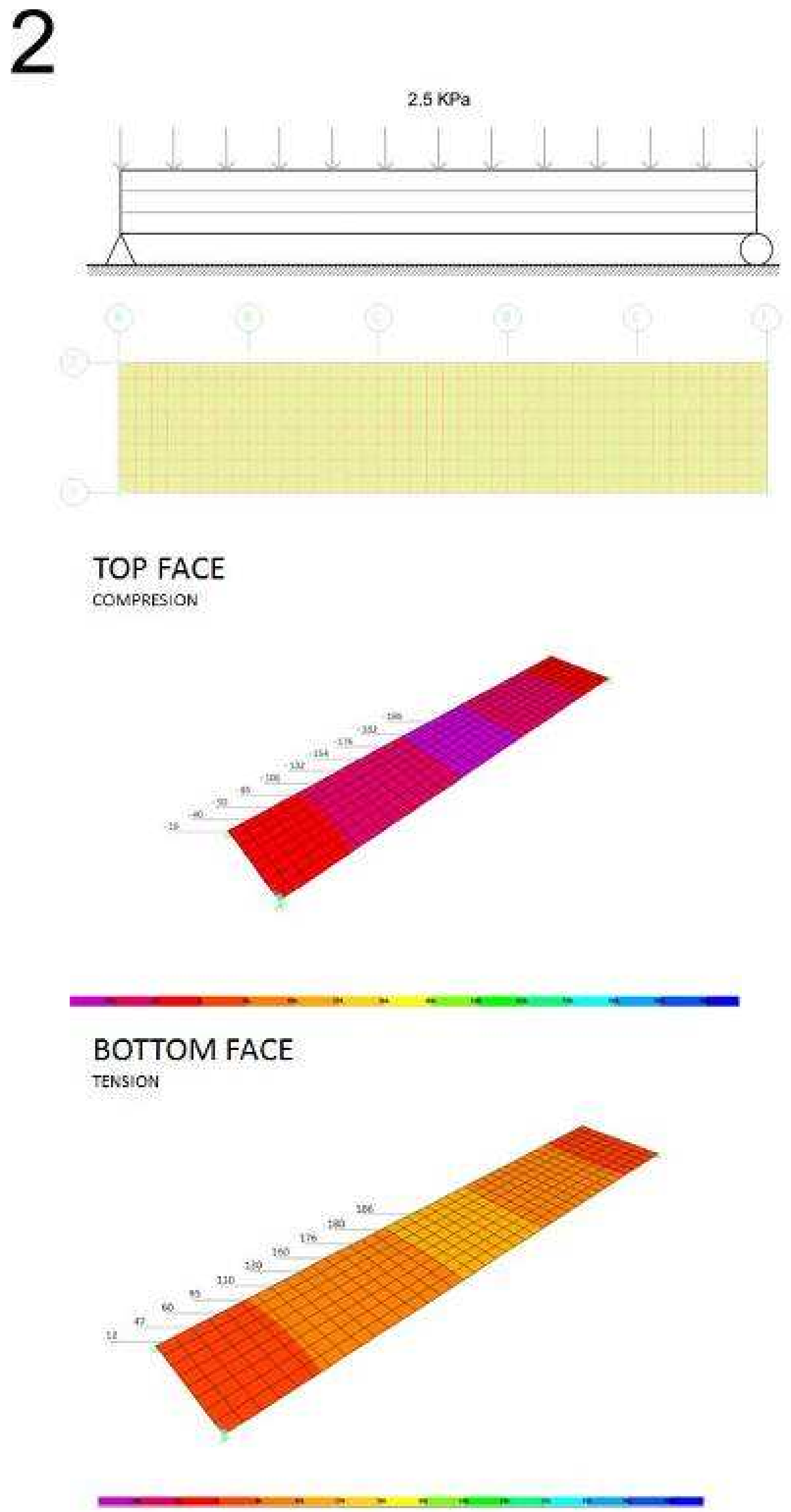


Fig. 45: Simulation 2.

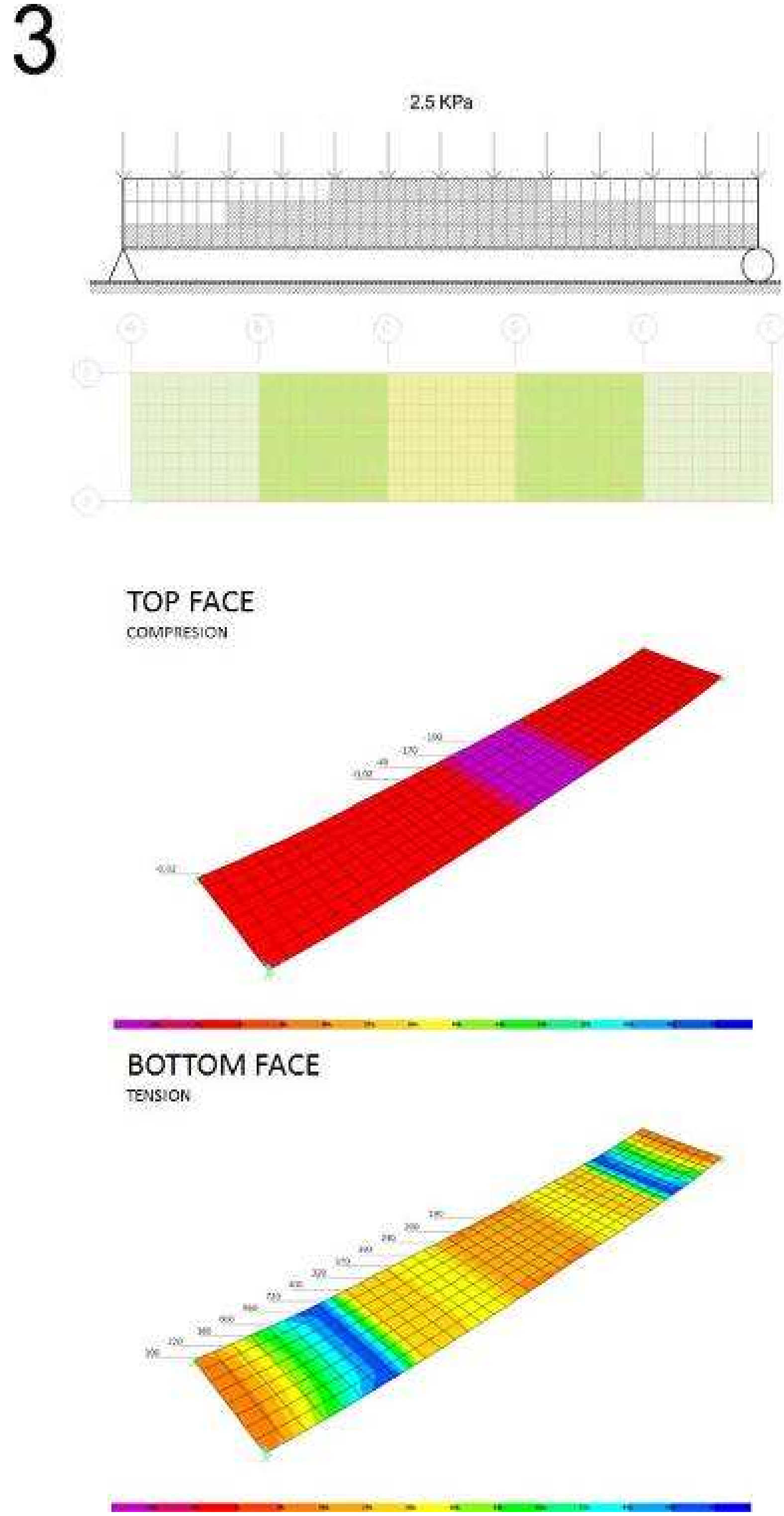


Fig. 46: Simulation 3.

8. Possible Applications

8.1. Heritage

One of the most important architectural traditions in Chile is defined by country towns with adobe row houses, that delineate streets with continuous facades.

In the 2010 earthquake, lots of individual houses that were part of this architectural tradition collapsed, breaking the continuity of the façade.

As described before, in the case of natural disasters the government will first provide an emergency house and then a final social housing solution to the former inhabitants of these collapsed houses.

The government, with the cooperation of construction companies, developed 30 different house typologies in order to accelerate the provision of the final house solution after the 2010 earthquake, from which each family can choose its own.

While it is important to deliver final housing solutions to the victims of natural disasters, it is equally important to note that the design of the emergency houses and permanent house solution does not consider the architectural tradition of the continuous facade ("fig. 47").

Because of its manufacturing flexibility and the possibility of making changes in the line of production, the prefabricated wood-based 3D printing technology proposed could easily adapt house typologies to particular contexts ("fig. 48").

Fig. 47: Picture of a final housing solution built in Curepto town two years after the 2010 earthquake.

Fig. 48: Possible adaptability response of the building technology proposed.

8.2. Response to Specific Environmental Demands.

As described, current mass social housing development is, in general, located in the peripheral areas of the city, and in most cases, the design of the housing solution is a repeated typology in a rigid urban grid.

Without considering local or particular contexts, this type of housing development happens all over the country (“fig. 49”).

It is well known that changes in the design would cause changes in the line of production, thus increasing cost.

But, do all families comprise the same number of people?
Do the families from the driest zones live under the same conditions as the families in the coldest zones?
Are the activities of older families the same as those of young families?

There are infinite types of family social, cultural and economic compositions, and also these vary according to geographic location.

After Hurricane Katrina struck New Orleans in 2005, the Field Office of Architecture used advanced digital fabrication processes to develop a design-built house for displaced residents of the city, varying the composition of each house’s roof according to each family’s needs.

The technology proposed would allow easy changes in design and in the line of production. In this way, projects could be suitable for particular contexts (“fig. 50”).

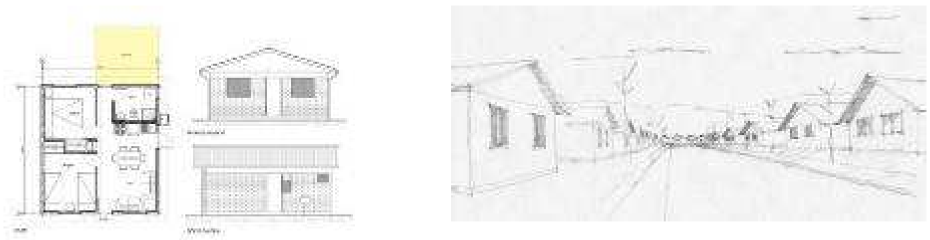


Fig. 49: Current social housing development in Chile. House typology repeated in a rigid urban grid.

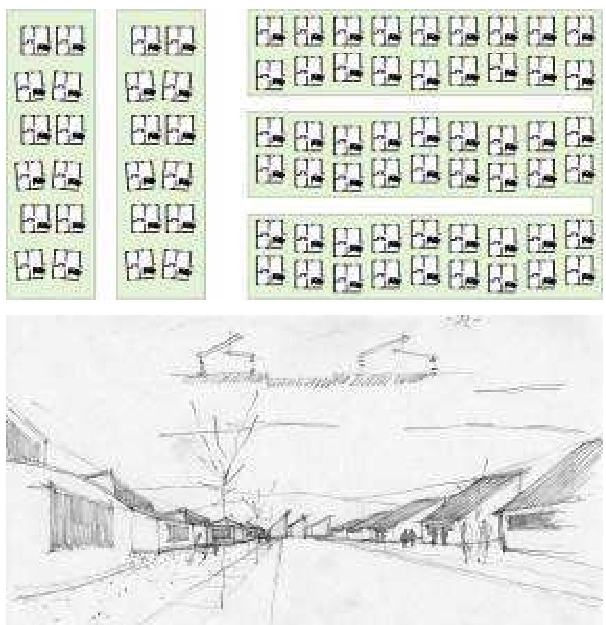


Fig. 50: Projects suitable for particular contexts.

8.3. Details.

This research proposes a prefabricated system. Usually prefabricated wood house systems consist of factory-made panels, which are then assembled on site.

One of the most critical parts related to the resistance and thermal performance of these prefabricated building systems, are the connections between the panels themselves and between the panels and other architectural components, such as doors or windows.

Jean Prouve, the famous French designer and manufacturer, designed for a couple of his projects in the late 1940s, rounded or continuous elements between walls and roofs. These designs were prefabricated 3D architectural elements that reduced or eliminated the problems related to the connections between panels, and between the panels and other architectural elements, in a prefabricated building system.

The technology proposed in this research could easily adjust the design and manufacture of the architectural elements to specific prefabrication strategies, and optimize the detail connection of the architectural elements to meet the resistance and thermal performance requirements. ("fig. 51").

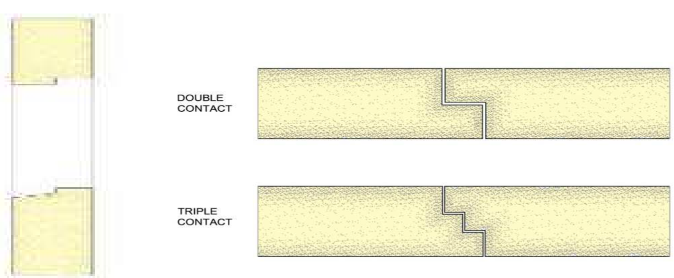


Fig. 51: Examples of possible detail prefabrication strategies with the proposed building system in order to optimize the structural and thermal resistance requirements of each specific project.

8.4. Contemporary Applications

The three pieces of full-scale 3D printing research described, show that it is possible to build a full-scale 3D printer, but such a printer and the current development of 3D print applications are only able to print one type of material.

The material limitations reduce the potential to produce prefabricated architectural elements that can be optimized according to specific requirements, such as structural and thermal performance. However, current development in the MIT MediaLab led by Neri Oaxman is attempting to 3D print materials with different densities, similar to what this project proposes. However, they are using concrete.

According to what this research proposes, the prefabricated wood-based 3D-printed architectural elements would comprise fibres and adhesives of different density.

But, how can we 3D print one architectural element with wood fibres that have different densities?
How does bonding work between wood fibres with different physical characteristics?

Because of these questions, future developments of this technology point to the forming and curing stages of the wood-based products as some of the biggest challenges.

To materialize the proposed building system, further development and research needs to look at specific areas.

9. Future Development

9.1. Matrix: Fibres, Adhesives and Additives

This research proposes prefabricated architectural elements with design and manufacturing configurations that may vary according to their particular requirements. This means that they need to be suitable for an infinite range of possibilities.

On the other hand, information on the possible wood fibres to be used, their characteristics when mixed with adhesives and possible additive applications are not sufficient for the development of this type of technology.

For future development, a matrix configuration is proposed as a starting point. This matrix divides the wood fibres into three categories according to their requirements: structural, insulation and finishing. At the same time, the matrix divides the adhesives into three categories according to their intended location in the prefabricated architectural element: exterior, semi-exterior and interior.

The Matrix proposed would always have the opportunity to incorporate possible additives to provide a better performance of the prefabricated elements ("fig. 52").

WOOD SPECIES			
ADHESIVE / FIBRES	EXTERIOR	SEMI EXTERIOR	INTERIOR
STRUCTURAL			
INSULATION			
FINISHING			
	ADDITIVES		

Fig. 52: Initial matrix proposal.

9.2. Material Optimization Software (MOS)

As described, it should be noted that the structural simulations for material optimization were made with the structural simulation software SAP 2000; this means that the structural results are reliable, but the thermal performance of the analyzed object is assumed to be correct by its material conductivity.

The simulations provide a close idea of the possible structural and thermal optimization of the full-scale wood-based 3D-printed prefabricated architecture elements, but future development will require the advent of material optimization software (MOS). .

The design of MOS should incorporate the proposed iteration system for optimization, and like SAP 2000 does with concrete and steel, could incorporate different types of wood fibre matrices, according to particular contexts (“fig. 53”).

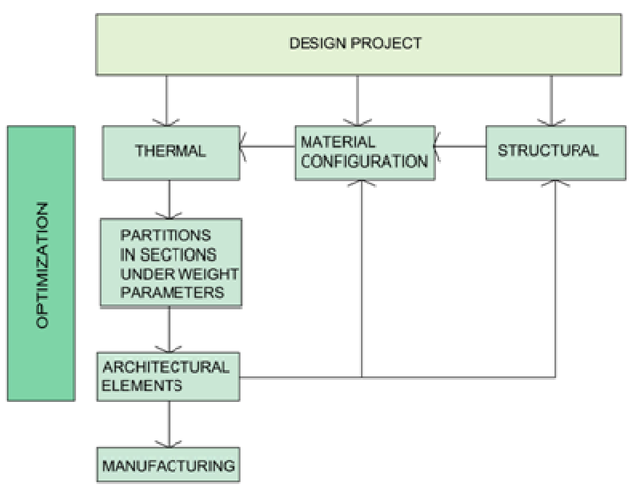


Fig. 53: Design of the material optimization software.

9. 3. Full Scale 3D Printer

9.3.1. Process

The first step to designing a full-scale wood-based 3D printer is to know what stages of the manufacturing process of the wood-based products the 3D printer is going to be part of, and what processes the material configuration will pass through.

The stages in which the 3D printer would be used are the mixture of fibres with adhesives and additives, and the fibre alignment. Next, the material would pass through the curing process.

9.3.2. Fibre Alignments

In the production of some wood fibre products, the fibre alignment is a fundamental part of the process.

In general, the alignment of fibres produces great material resistance, but the manufacture of products with fibre alignment is limited to a unique design. Possible changes in the design of the fibre alignments are extremely limited and slow, and this is one of the major reasons why structural wood-based products are related to a mass-produced standard size.

For the manufacture of a full scale wood-based 3d printer, this research points to the study of possible existing solutions that may be suitable for the production of infinite configurations.

9.2.3. Multilayer Products

Today there are existing solutions for the development of multilayer products that could be suitable to what this research proposes. For instance, some paper production machines are now able to produce multilayer fibre products.

These multilayer fibre products specify different types of fibres according to function. For example, some magazine paper has a layer of fibres for structure in the centre, and a layer of fibres for finishing at the sides.

9.2.4. Machines-First Approach. (Bonding-Curing)

As described, the full-scale wood-based 3D printer would need to process three different stages that wood-based products pass through: mixing, forming and curing. The three different stages present different questions that need to be studied and answered in order to advance a possible blueprint for the machine:

Would the mixing between adhesives and fibres happen before the forming stage, as in traditional wood-based products, or would it occur after the forming stage, as in the case of traditional 3D printers?

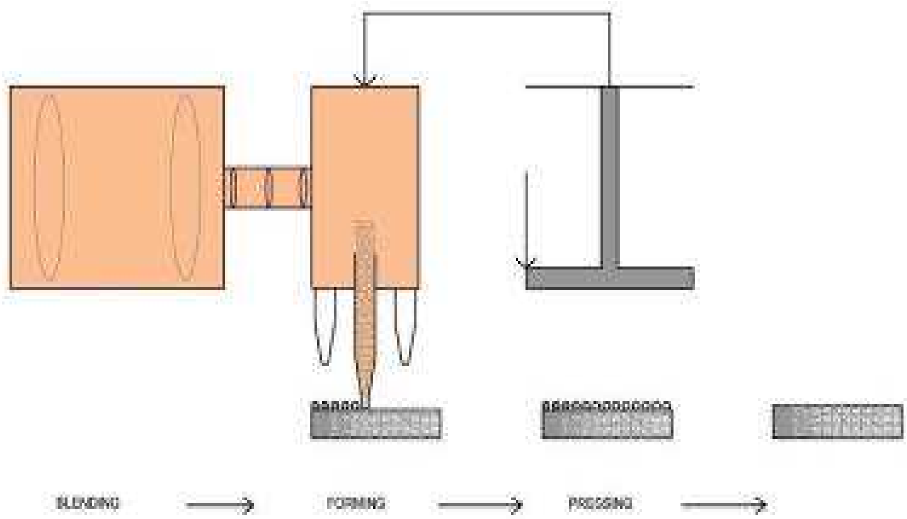
Would the forming stage be controlled by trowels or by different nozzles with different sizes?

For curing, what pressure and temperature would the architectural elements require in order to solidify?

As an example of the possible machine design approaches, the images of Fig. 54 describe two different design proposals for a wood-based full-scale 3D printer. In the case of the printer pictured on top, the fibres would be transported pre-mixed into the head box of the 3D printer. By contrast, the proposed machine pictured below would mix the fibres in the head box.

In both proposed machines the control of the deposition of different fibres would be achieved through the use of different nozzles.

The main difference between the proposed machines is that the one at the top will press the entire layer of deposited fibres at once by a hot press plate, and the one below will press the fibres immediately after they are extruded by a roller press that follows the nozzle.



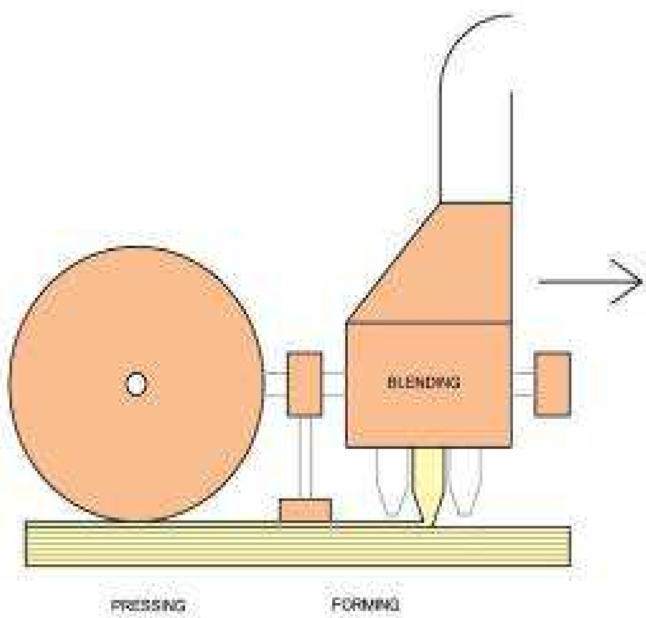


Fig. 54: Initial machine design approach.

10. Cost – Benefit Analysis and Homeless Market

It is important to note that the technology this research proposes is very expensive. But, considering that 500,000 Chileans are homeless, and that the government builds an average of 60,000 social houses per year, most of low architectural quality, this kind of technology investment appears profitable in the long run. This will be especially true if a local sustainable industrial network among social housing, renewable forests and wood products develops (“fig. 55”).

Also, if the local market for wooden social housing development is not enough, export possibilities are always open, especially considering the 54,000,000 homeless families in Latin America, or in other countries such as India, with 78,000,000 homeless.
In Canada there are only 150,000 homeless people, but the cost for the government in emergency services for these homeless people is $4.5 to $6 billion per year.

In conclusion, it is clear that the major global problem of homelessness points to the lack of affordable housing. As discussed, wood-based 3D printed housing development could be an alternative and cost-effective solution to the emergency and social housing challenges of today.

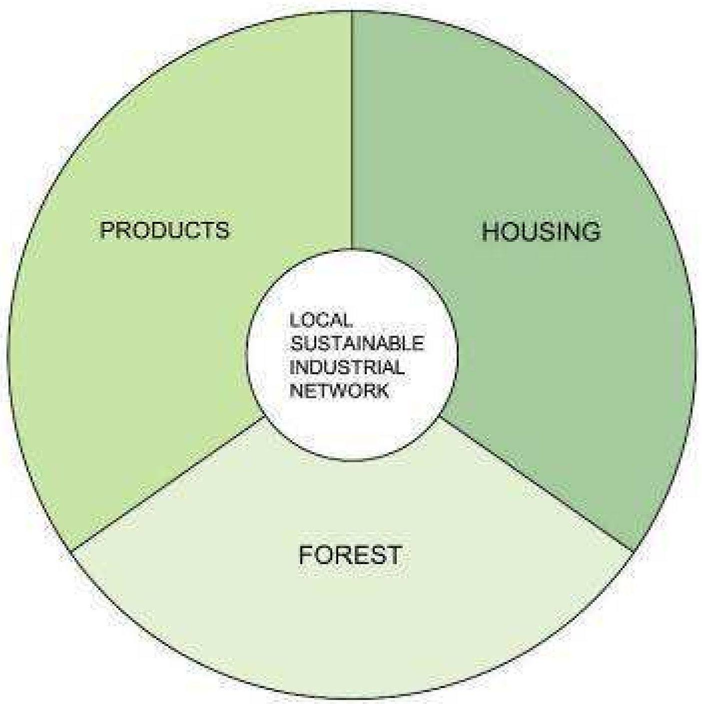


Fig. 55: Local Sustainable Industrial Network.

Bibliography

Arteaga, Felipe. 2012. *2012 Annual Report*. Santiago, Chile: Un Techo Para Chile.

Baldassare, M. 1992. "Suburban Communities." *Annual Review of Sociology*: 475–494.

Branko, Kolarevic. 2003. *Architecture in the Digital Age: Design and Manufacturing*. New York, NY: Spon Press.

Bravo, Luis. 1974. *Diagnostico De La Actividad Constructora En Chile y Rol De La Construcción Industrializada De Vivienda. Seminario: Industrialización De La Construcción En Chile*. Instituto de la Vivienda Facultad de Arquitectura Pontificia Universidad Catolica de Chile.

Bustamante, Waldo. 2009. *Guia De Eficiencia Energetica Para La Vivienda Social.* 333rd ed. Santiago, Chile: Ministerio de Vivienda.

Bustamante, Waldo, and Felipe Victorero. 2011. *Estudio Del Comportamiento Térmico De La Vivienda De Emergencia En Chile*. Un Techo Para Chile. http://www.untechoparachile.cl/cis/images/stories/Tesis/Vivienda/Estudio%20del%20comportamiento%20t%C3%A9rmico%20de%20la%20mediagua.pdf.

Buswell, R.A., Soar, R.C., Gibb, A.G.F., and Thorpe, A. 2007. "Freeform Construction: Mega-scale Rapid Manufacturing for Construction." *Automation in Construction* 16: 224–231.

Dini, Enrico. 2008. "Method and Device for Building Automatically Congromerate Structures."

Ferré, Albert, and Tomoko Sakamoto, eds. 2008. *From Control to Design*. Actar.

Freire, Juan. 2007. "Sostenibilidad Urbana: Hacia Un Planeta Urbano: Desarrollo, Urbanización y Medio Ambiente." http://www.nomada.blogs.com/jfreire/2007/03/sostenibilidad__1.html.

Gonzalez, Felipe. 2010. "Hitos y Desafíos Del Sector Forestal." *Lignum Magazine, Number 121*, September.

Khosnevis, Behrokh. 2009a. "Technics for Sensing Material Flow Rate in Automated Extrusion."

———. 2009b. "Metering and Pumping Devices."

———. 2010a. "Gantry Robotics System and Related Material Transport for Contour Crafting."

———. 2010b. "Fluid Metering Device Using Free-Moving Piston."

———. 2010c. "Dry Material Transport and Extrusion."

———. 2010d. "Contour Crafting Extrusion Nozzles."

———. 2011. "Extrusion of Cemetitious Material with Different Curing Rates."

Kolarevic, Branko, ed. 2003. *Architecture in The Digital Age: Design and Manufacturing. New York: Spon Press.* New York: Spon Press.

Mattheck, C. 1998. *Design in Nature: Learning from Trees*. Berlin ; New York: Springer-Verlag.

Ministerio de Desarrollo Social. 2010. *Caracterizacion Socio-economica Nacional*. Santiago de Chile.

Ministerio de Vivienda. 2004. *El Deficit Habitacional En Chile: Medicion De Los Requerimientos De Vivienda y Su Distribucion Espacial*. Politica Habitacional. Santiago, Chile: Ministerio de Vivienda.

Ministerio de Vivienda. 2010. "Ordenanza General De Urbanismo y Construccion." Gobierno de Chile, 2010.

Navarro, Mario. 2005. "Housing Finance Police in Chile: The Last 30 Years." *Land Lines Magazine. Number 334*, July.

Schittich, Chiristian. 2012. "Editorial." *Detail Magazine. Review of Architecture, Number 52*.

Tironi, Rodo. 2003. *La Nueva Pobreza En Santiago: Precariedad, Vivienda y Capital Social En Santiago De Chile 1985-2001*. Santiago, Chile: Predes Editores.

UNICEF. 2003. "Unicef-Chile-Statistics." *UNICEF*. http://www.unicef.org/infobycountry/chile_statistics.html.