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ALINE MACHADO DE CAMPOS SANTORO

CONSERVATION OF MODERNIST ARCHITECTURE THROUGH THE VISUAL ANALYSIS OF PHYSICAL DECAY

Brasília
2019

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Dissertação de Mestrado apresentada como requisito parcial para obtenção do grau na área de tecnologia no Programa de Pós-Graduação da Faculdade de Arquitetura e Urbanismo da Universidade de Brasília – UnB.

Área de Concentração: Tecnologia, Ambiente e Sustentabilidade

Linha de Pesquisa: Estruturas e Arquitetura

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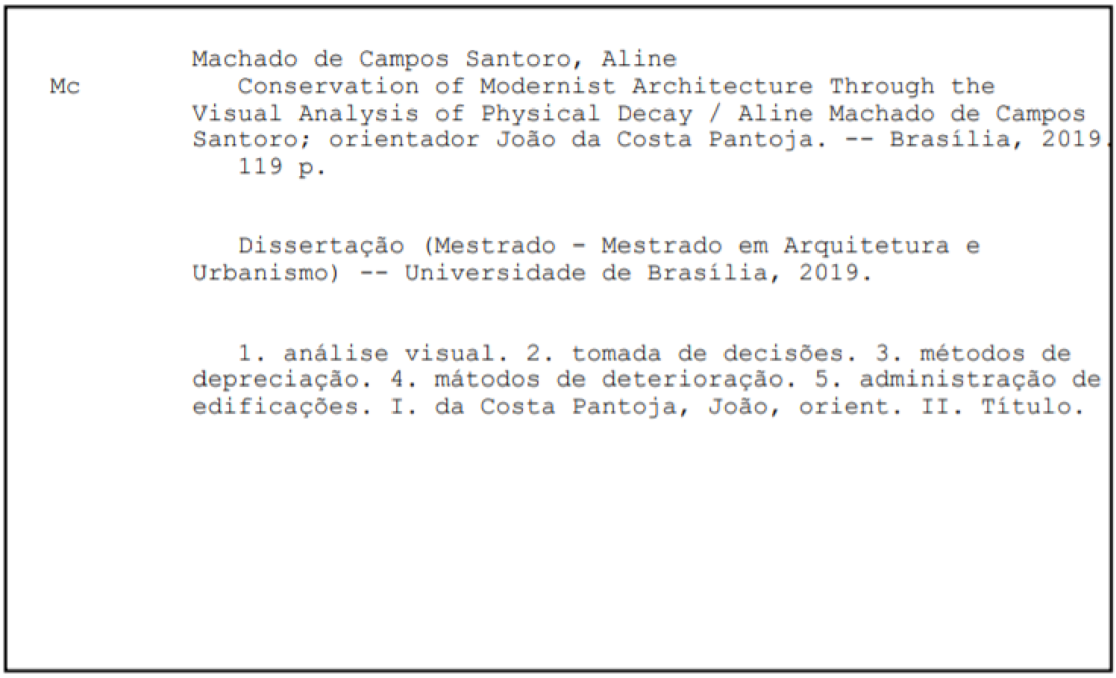

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To my friends, without whom I would never have finished.

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ABSTRACT

Most modernist architecture in Brazil have experienced some degree of decay. The conservation of our national architectural heritage is constantly threatened by the inefficiency, or even lack of, conservation, maintenance and restoration programmes, as well as the imminent end of the projected lifespan for the first modernist constructions. For this scenario, Visual Analytics can become a powerful tool in the hands of a facilities manager. Its purpose is to accelerate rapid insight into the internal structure of data and causal relationships therein, through the use of visual representations and interactions, and to enable discoveries, explanations and facilitate decision making. The visualisation capabilities of Building Information Modelling and its ability to incorporate performance-over-time data make it the strongest tool for construction building analytics today. As such, this research project will demonstrate how predictive simulation can contribute to the decision-making process for Historical Facilities Management. The merging of these three areas – deterioration and depreciation analysis in heritage management, decision support in facilities management and the visual analytics of building information modelling – will allow us to not only register current and future heritage status, but predict the impact of future management decisions. The current research proposes a hybrid methodology from the compilation of three methods – the parametric GDE-UnB physical deterioration method, the parametric Dutch Standard for defect importance and the Ross-Heidecke financial depreciation method – in mapping a section of the University of Brasilia Central Science Institute. The results were subdivided into four main stages: the inspection and mapping of element pathologies through physical inspection and photographic evidence; the scripting, comparison and analysis of different degradation and depreciation methods, from which originated a hybrid methodology; the graphic mapping, representation and visual analytics of the original methodology on the use case model and the scenario simulations for decision making.

Keywords: HBIM; decision support; depreciation methods; deterioration methods; FM practices.

RESUMO

A maior parte da arquitetura moderna brasileira tem passado por algum grau de deterioração. A conservação da herança nacional arquitetônica é constantemente ameaçada pela ineficiência, ou até mesmo falta, de programas de conservação, manutenção e restauração, assim como o fim iminente da vida útil projetada para as primeiras construções modernistas. Para esse cenário, a Análise Visual pode se tornar uma ferramenta poderosa nas mãos de um gerente das edificações. Seu propósito é de acelerar uma percepção rápida dentro da estrutura interna de dados e relações causais internas, através do uso de representações e interações, e permitir descobertas, explicações e facilitar tomadas de decisão. As capacidades de visualização do BIM e a sua habilidade de incorporar informações de performances através do tempo o torna a ferramenta mais forte para a análise de construções atualmente. Assim, almeja-se demonstrar como uma simulação de previsão pode contribuir para o processo de tomada de decisão para o gerenciamento de instalações históricas. A fusão dessas três áreas – análise de deterioração e depredação em gerenciamento do patrimônio, suporte para tomada de decisões no gerenciamento das edificações e a Análise Visual do BIM – vai permitir não apenas registrar o status presente e futuro de herança, mas prever o impacto de decisões de gerenciamento futuras. A presente pesquisa propõe uma metodologia híbrida da compilação de três métodos – o método de deterioração física GDE-UnB, o Método Holandês de criticidade da patologia e o método de depreciação financeira Ross-Heidecke – no mapeamento de uma seção do Instituto Central de Ciências da Universidade de Brasília. Os resultados foram subdivididos em quatro estágios principais: a inspeção e mapeamento de patologias elementares através de inspeção física e evidências fotográficas; a criação de *scripts*, comparação e análises de diferentes métodos de degradação e depreciação, dos quais originou-se uma metodologia híbrida; o mapeamento gráfico, a análise visual e a representação da metodologia original no uso do estudo de caso e das simulações de cenários para a tomada de decisão.

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LIST OF ABREVIATIONS

AEC	Architecture, Engineering and Construction
BAS	Building Automation System
BIM	Building Information Modelling
CEPLAN	University Centre for Planning
CMMS	Computerised Maintenance Management System
CR	Condition Rating
CS	Conservation Status
D	Damage Degree
DOCOMOMO	International Committee for Documentation and Conservation of Building, Sites and Neighbourhood of the Modern Movement
EMS	Energy Maintenance System
ESL	Estimated Service Life
Fi	Importance Factor
FM	Facilities Management
Fp	Ponderation Factor
Fr	Relevance Factor
G_{de}	Element Deterioration Degree
G_{df}	Element Family Deterioration Degree
GIS	Geographical Information System
HBIM	Heritage Building Information Modelling
ICC	Central Science Institute
ICOMOS	International Council of Monuments and Heritage
IPHAN	Brazilian National Institute for Historical and Artistic Heritage
ITcon	Journal of Information Technology in Construction
kg	Global deterioration factor
kie	Individual element deterioration factor
kif	Individual family deterioration factor
O&M	Operation and Management
SBPC	Brazilian Society for Scientific Progress
SSL	Standard Service Life
UnB	University of Brasilia
UNESCO	United Nations Educational, Scientific and Cultural Organizations
VA	Visual Analytics

1 INTRODUCTION

The growing concern for architectural heritage preservation and conservation in Brazil has recently generated a series of studies regarding its service life, degradation status and pathologies (ASSOCIAÇÃO BRASILEIRA DE NORMA TÉCNICA, 2013). Modernist architectural heritage has been specially affected by the short service life of reinforced concrete and non-existent governmental maintenance budgets. Most modernist constructions in Brazil have already reached sixty years of existence. Many of which lack appropriate periodic maintenance.

There is a large proportion of modernist structures in a state of physical depreciation and threatened structural performance. For this reason, scenario simulation has become essential through the precise record of the construction's current status, the qualitative and quantitative physical depreciation evaluation, and the pathological progression prediction.

Cultural heritage investigation and application can benefit from digital technology using two main approaches to aid in traditional investigation methods: improving efficiency and solving complex problems or providing completely new methods of investigation based on cultural heritage digital information. Either way, 'it helps to acquire information related to the environment, mapping, status and deterioration of cultural heritage and manages the investigation information through databases, thus providing detailed information for developing a conservation plan' (LU; PAN, 2010 p. 90).

However, it is well known that building operations and maintenance costs during service life can extend to many times the construction cost (BECERIK-GERBER et al., 2012). It is therefore essential to influence decision-makers to see the importance of regular conservation processes by demonstrating the monetary consequences of postponing decisions.

In this way, Visual Analytics (VA) can become a powerful tool in the hands of a facilities manager. Most Operation and Management (O&M) decisions today are made using a text-based data application, such as the Computerized Maintenance Management System (CMMS). However, due to complex interrelations between building components and systems, changing environmental factors and the variety of building components, it can be extremely difficult to determine failure root causes in CMMS. Spatial information distribution in a Building Information Modelling (BIM) model can greatly benefit root cause detection by facilitating simultaneous visualisation of a large amount of lifecycle data. Thus, VA combines ‘automated analysis techniques with interactive visualization for effective understanding, reasoning and decision making on the basis of very large and complex datasets’ (MOTAMEDI; HAMMAD; ASEN, 2014).

Visualisation holds strong potential for the field of construction engineering, as it ‘facilitates the communication of data which may have otherwise remained in an unintelligible form’ (PILGRIM, 2003). It is mainly divided into two main areas: Construction Information Communication and Construction Simulation, which includes the simulation of structure, fire performance, environmental impact, acoustics, maintenance, airflow, thermal analysis and automation systems. The visualisation capabilities of BIM and its ability to incorporate performance-over-time data make it the strongest tool for construction building analytics today.

Historic Building Information Modelling (HBIM) and Facilities Management (FM) can therefore act as important tools in achieving this process. Although heavily used during modelling and construction stages, Becerik-Gerber et al. (2012) indicates that the use of BIM can “support and enhance other functions of FM through its advanced visualization and analysis capabilities”. However, we do not yet have a total understanding “as to where BIM can provide benefits to FM practices, what some of the challenges are, and what the expected value is”.

Volk, Stengel and Schultmann (2014) indicate that FM practices are still focusing on recently completed constructions with existing BIM models, as opposed to developing an as-built model for existing structures. While buildings with existing BIM models face a number of challenges regarding data standardisation and system compatibility, heritage FM requires a complete as-built analysis and data migration into open BIM or FM systems (PATACAS et al., 2015).

With regards to HBIM, despite the fact that considerable advances have been developed concerning documentation strategy through modelling techniques

(FAI; RAFEIRO, 2014 and BANFI; FAI; BRUMANA, 2017), data-acquisition (CHENG; YANG; YEN, 2015), and maintenance information integration (MOTAWA; ALMARSHAD, 2013), existing buildings concerns, such as deterioration modelling, condition assessment systems, and failure modelling in HBIM, are still at very early stages (MOTAMEDI; HAMMAD; ASEN, 2014).

1.1 Field Contributions

In order to satisfy the need for decision-making tools, the merger of these three areas was needed. While VA can provide a visual record of current and future degradation states, the depreciation and deterioration methods used in heritage management can provide FM the required prediction tools for effective decision making. By visualising critical areas and precisely determining the cost difference of executing preventive maintenance now and reparative maintenance in the future, it is possible to predict the consequences of different maintenance decisions and decide on the best one according to its cost-benefit ratio.

We believe that recent developments of the Ross-Heidecke depreciation evaluation model, such as Pimenta (2011) and Pereira (2013), along with deterioration analysis methods, such as the parametric GDE-UnB (PANTOJA et al., 2018) and the Dutch Standard, can be used to graphically simulate building depreciation according to a number of chosen parameters, such as structure and infrastructure. Through visual analysis, we were able to compare the application of the GDE-UnB and the Dutch Standard methods, determine which is the most efficient and analyse its use within the Ross-Heidecke model. We were then able to perform what-if analysis according to different scenarios and possible maintenance decisions. This scenario analysis helps the conservation decision-making process by demonstrating the consequences of maintenance decisions, or lack thereof.

This research use case encompasses a section of the University of Brasilia Central Science Institute, which was built from 1963 to 1975 with a precast-prestressed isostatic structure. Five structural parameters were chosen to calculate general degradation: interior pillars, t-section beams, exterior pillars, square-section beams and gutter-beams. The formulas were manipulated according to maintenance decisions to develop predictive scenarios by using graphic parametric software, such as Rhino 3D and Grasshopper.

1.2 Motive

Reinforced concrete is a concatenated engineered material, and as such, does not last forever. FM practices are, therefore, essential to modernist architectural heritage, as it is mainly made from reinforced concrete. However, in Brazil, modernist architectural heritage is government-managed and its conservation is prey to endless bureaucracy, which hinder all maintenance and causes further degradation. Governmental maintenance budget for architectural heritage is non-existent. It has become evident that governmental FM decision-makers lack the necessary tools to visualise and understand the consequences of their decisions. For this purpose, depreciation analysis methods require further development and standardisation, such as the inclusion and consideration of deterioration methods.

1.3 Problem

Brazil’s capital, Brasília, is an entirely modernist city built almost entirely out of reinforced concrete in the 60’s and 70’s where a large number of buildings are now considered World and National Heritage. Considering that, at the time of construction, the Brazilian regulation concerning reinforced concrete structure durability was still undeveloped, many of these buildings are reaching the end of their service life. Furthermore, although generally accepted that preventive maintenance can prolong service life, annual governmental heritage maintenance budget is non-existent and there is no way to estimate the financial benefits of preventive maintenance.

1.4 Hypothesis

By visually simulating the consequences of different maintenance decisions on service life, such as replacing window frames and rainwater gutters, or providing regular and appropriate maintenance, it is possible to see the impact on the depreciation of heritage buildings.

1.5 Objectives

1.5.1 Main Objective

- Develop a hybrid building depreciation method based on element deterioration and the merging of the Dutch Standard, the parametric GDE-UnB and the Ross-Heidecke methods.

1.5.2 Secondary Objectives

- Provide governmental Facilities Management (FM) decision-makers with the necessary tools to visualise and understand the consequences of their decisions, or lack thereof.

- Research current status of Facilities Management (FM) and Heritage Building Information Modelling (HBIM),

- Study possibility of inputting deterioration values obtained from the GDE-UnB and the Dutch Standard into the Ross-Heidecke method,

- Develop advanced visualisation and analytic capabilities of depreciative predictive simulation.

1.6 Methods

This research began with becoming acquainted with Pimenta's (2011) and Pereira's (2013) research on the Ross-Heidecke formula, as well as testing it on a number of use cases previously published (OLIVEIRA et al., 2017b). In order to improve the formula's projected accuracy, deterioration methods, such as the GDE-UnB (CASTRO, 1994) and the Dutch Standard (STRAUB, 2009) were analysed as a means of supplying the formula a more objective conservation status.

As part of the literature review, a historic research was carried out concerning world heritage modernist architecture in Brazil, in order to demonstrate the necessity of implementing these models into these structure's facilities management. In order to use BIM to supply Heritage FM decision-makers with the appropriate tools, we attempted to identify the possible uses of the deterioration and depreciation methods mentioned within growing interest in HBIM, FM applications and heritage conservation. In order to do so, we carried out a non-exhaustive literature review involving FM in HBIM, over the last six years through scholastic web search engines and citation indexing services, such as Web of Science, Google Scholar and the Brazilian *Capes Periódicos*. Since the theme is very recent, no books will be referenced during this section.

The research was narrowed to eleven papers from the Elsevier publisher, four papers from the Journal of Information Technology in Construction (ITcon), five papers from the International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences Symposiums and fifteen papers obtained from previously selected paper's references.

A section of the University of Brasilia Central Science Institute (ICC) was chosen as use case since we had recently participated in its complete inspection, according to which, we were able to assign individual depreciation state factors to each of the following construction elements: interior pillars, t-section beams, exterior pillars, square-section beams and gutter-beams. We were also able to quantify certain characteristic qualities, such as execution, use, interior environment and maintenance along with the building's history and plans.

Since all analysed elements are pre-fabricated reinforced or pre-stressed concrete, they were estimated to have the same cost per volume and as such the volume of each element also represents its cost with regards to the entire structure. The current age, the Standard Service Life (SSL) and the Estimated Service Life (ESL) were then determined as usual. The deterioration methods came into play when assigning a Conservation Status (CS). Each element was subdivided into a mesh of voxels (10x10x10cm cubes) and each damage was mapped.

The parametric Dutch Standard and the parametric GDE-UnB (PANTOJA et al., 2018) methods were then used separately and together in order to determine the deterioration degree for each element and then compared. The GDE-UnB was calculated according to the intensity and ponderation factors of each defect, while the Dutch Standard was used to determine a Condition Rating (CR) for each voxel according to its volume in relation to the entire element, its importance and its intensity. Both were then inputted into the Tuutti chart to calculate a D, which in turn was inputted into the GDE-UnB formula to calculate a deterioration degree (G_{de}) for each element. The results were then compared to determine the most accurate method, as explained in Section 6.3.

The G_{de} based on a hybrid approach between the parametric GDE-UnB and the Dutch Standard was chosen due to the fact that it takes into account defect volume. It was thus inputted into the Ross-Heidecke formula in place of the CS to calculate individual depreciation factors for each element (kie), whose average and weighted mean in turn provided the depreciation factors for each element family (kif) and the global depreciation factor (kg) respectively.

The building was then modelled in a computer-aided design application software (*McNeel's Rhinoceros 3D*), after which a graphical algorithm editor (*McNeel's Grasshopper 3D*) was used to associate different construction elements to the initial formulas and generate a parametric visualisation of deterioration degrees, condition ratings and individual and global depreciation status through a gradient of green to red.

A variety of scenarios were then simulated according to different maintenance decisions and potential depreciation evolutions, which in turn generated parametric visualisation of each scenario's individual and global depreciation status through a gradient of green to red. We were then able to quantify the theoretical economic benefits of each maintenance decision.

1.7 Dissertation Structure

CHAPTER 1 – Introduction

The introduction begins with research context, followed by possible field contributions, the driving motive, the research problem and its respective hypothesis. General and specific objectives are then laid out and methods are discussed.

CHAPTER 2 – Modernist Architecture Preservation

The second chapter is divided into three sections. The first discusses the challenges facing modernist architectural heritage today and discusses conservation and maintenance guidelines. The second focuses on the city of Brasília, as it was completely constructed during the modernist period. The last section describes the University of Brasília and the use case context.

CHAPTER 3 – VISUAL ANALYTICS

The chapter on Visual Analytics (VA) explains the concept and why it is important within the construction industry. It details the VA's role within BIM applications both for Depreciation Analysis and the documentation and restoration of modernist architecture. Furthermore, it explores current BIM uses both in facilities management and historical preservation.

CHAPTER 4 – Building Depreciation and Deterioration Methods

This chapter expands on building depreciation and deterioration analytical methods. It first explores linear, quadratic and the Ross methods, then expands on the Ross-Heidecke method and its future developments. Lastly, it explains the GDE-UnB and the Dutch Standard deterioration methods and proposes a hybrid method through which all further calculations will occur.

CHAPTER 5 – Use Case

CHAPTER 6 – Results

CHAPTER 7 – Conclusion

2 MODERNIST ARCHITECTURE PRESERVATION

2.1 Modernist Architecture

The new technologies of the 19th and 20th centuries changed design and construction thinking. Industry replaced craftsmanship, structures were no longer supported by rock, but on thin vertical planes, and windows became entire facades. New structural material enabled light and transparent structures. While the first preservation discussions revolved around ancient constructions and war-ravaged monuments, new buildings represented innovation in an affirmative manner (SILVA, 2017). Architectural transformation did not only reflect technological innovation, but also social revolution. It would give new meaning to mass-produced art, which would later be widely distributed due to city expansion and specific demands (CARVALHO, 2005).

The Industrial Revolution introduced a mass-production spirit, in which every branch of the building industry tended to transform natural raw materials and produce new ones. Cements, limes, steel girders, sanitary fittings, piping, insulating materials, water-proofing compositions and ironmongery are ‘dumped in bulk into buildings in the course of construction, and are worked into the job on the spot’ (LE CORBUSIER, 1931). Building aesthetics absorbed the new industrial aesthetic, based on numbers and order. According to Le Corbusier:

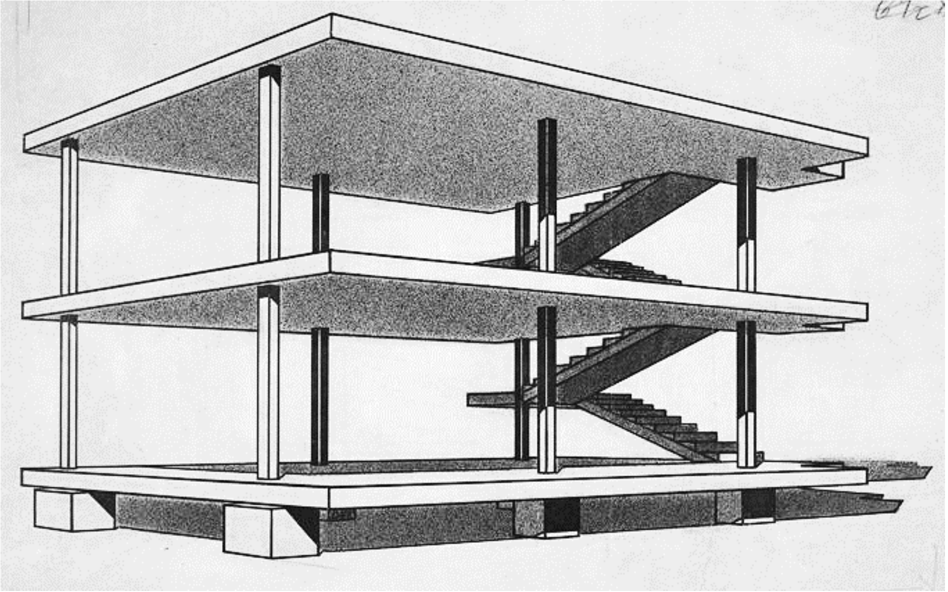
> Industry, overwhelming us like a flood which rolls on towards its destined end, has furnished us up with new tools adapted to this new epoch, animated by the new spirit. Economic law unavoidably governs our acts and our thoughts. The problem of the house is a problem of the epoch. The equilibrium of society today depends upon it. Architecture has for its first duty, in this period of renewal, that of bringing about a revision of values, a revision of the constituent elements of the house. Mass-production is based on analysis and experiment. Industry on the grand scale must occupy itself with building and establish the elements of the house on a mass-production basis. (LE CORBUSIER, 1931 p. 227)

The urgency and severity of post-World War I urban and residential challenges in Europe could only be resolved by an architecture based on new technology, new architectural form and new design methods. Construction speed and economy of resources became essential due to this strong social component, which in turn induced in Modernist Architecture the rule of formal and constructive rationality, standardisation and pre-fabrication (ROCHA, 2011).

Industry supplied architecture with new laws. Construction innovations were no longer able to sustain the old ‘styles’. The ancient and forgotten architecture laws established on mass, rhythm and proportion were reintroduced by the new industrial programmes and construction methods. ‘Steel and concrete have brought new conquests, which are the index of a greater capacity for construction, and of an architecture in which the old codes have been overturned’ (LE CORBUSIER, 1931).

Thus, the Modernist Movement was created not just as a mere architecture style aimed at breaching tradition, but an economic, social and technical product of the Industrial Revolution. Its foundation was therefore driven by the debates surrounding urban and social transformation and the revolution in architectural production.

Figure 1: Le Corbusier’s Maison Dom-Ino (http://www.fondationlecorbusier.fr)

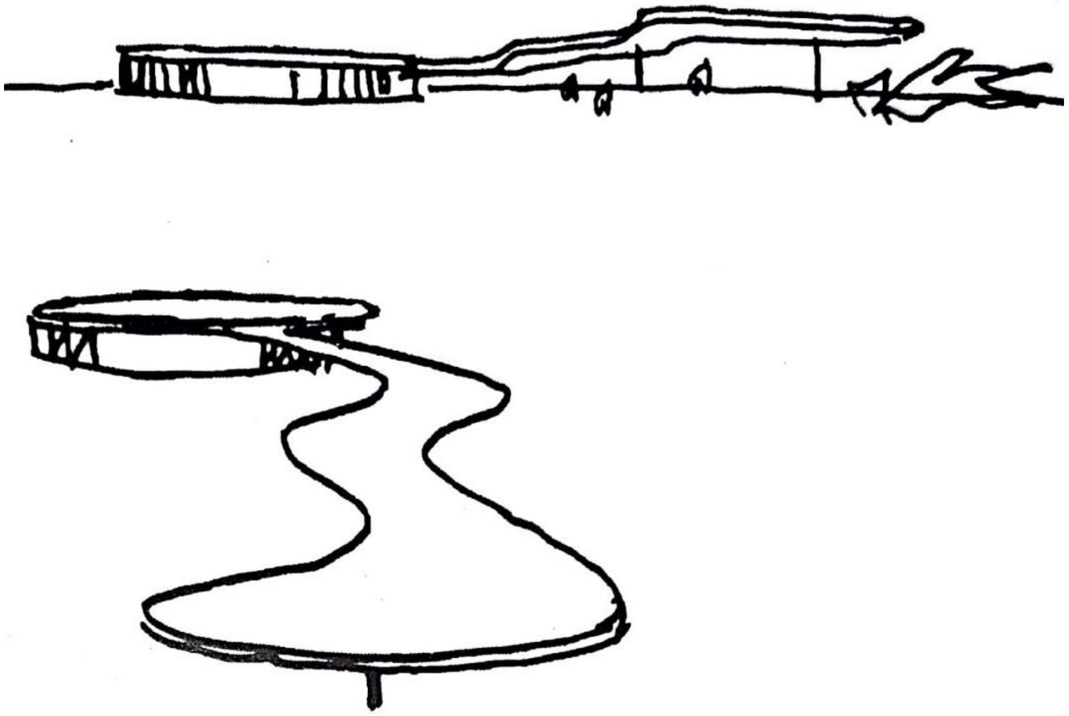


New materials enabled autonomy between structure and cladding with the creation of a homogeneous grid of superimposed pillars and slabs, whose greatest expression is embodied by Le Corbusier’s Maison Dom-Ino (Figure 1), whose construction process permitted an extensive and rhythmic layout. This is where the true value of the mass-produced house comes into play: by linking the rich man’s and the poor man’s house. In other words, the method can be applied to a middle-class house at the same price per square foot as a simple workman's house because everything is mass-produced: windows, doors, cupboards; all with a common unit of measurement.

Construction materials and expertise evolved simultaneously with Modernist Architecture production: new materials were developed, traditional materials were used in new ways and construction details and components were created. Experimental processes were adopted and components were strained to their maximum, with no knowledge of how new construction solutions would act over time.

Reinforced concrete structures were largely responsible for the beauty and delicacy of modernist buildings. On account of it being a new and very malleable material, concrete made it possible to decorate the urban space with innovative curves, which, according to Niemeyer (1978), resembled the curves of the female body (Figure 2). However, at the time, reinforced concrete was thought analogous to stone constructions, eternal and immutable, immune to deterioration.

Figure 2: Niemeyer's drawings inspired by the female body. (NIEMEYER, 1978)



In Brazil, contrary to what was happening in Europe, Modernist Architecture was established due to government commissions. The economic growth of the 1930's stimulated the Vargas government to leave its mark on the architectural form of the country's capital, which at the time was Rio de Janeiro, with the construction of new ministry buildings. However, the selection of the form which would represent not only Rio de Janeiro but the 'New State', would precipitate many disputes and would come to depend on the support of non-architectural allies and the mobilisation of public opinion. According to Cavalcanti (2006):

> Modernist Brazilian architects conquered the dominant position thanks to several movements which ascertained their superiority to their academic and neo-colonialist competitors within two field extremities: social and erudite. The elimination of ornaments, the exposed structure, the open floor-plan, the prototype and the possibility of industrial reproduction were presented as ethical motives of the Modernist Movement. Not only would the houses of both the rich and the poor be similarly arranged, but after the arrangement, there would be the possibility of mass-producing worker houses.[1] (CAVALCANTI, 2006)

Modernist form was no longer about style; it became a political and social necessity. With the mass-produced house, architects expected to re-educate the poor on the correct way of living, thus embodying a social campaign which would help to distinguish the Movement and delineate its field. Modernist facilities became the domestic worker's liberation instrument. The 'Brazilian dwelling machine', which during the Colonial period depended on slaves for everything, would give way to mass-produced flexible and efficient living spaces.

The capacity to create monuments, on the other hand, contributed to modernist prominence at an erudite level. It is that which came to distinguish Brazilian modernists and secure their dominance over other styles of the time. The political power obtained by modernist architects would give characters such as Lúcio Costa and Oscar Niemeyer the power to arbitrate which monuments would accede to the national architectural pantheon and which would not.

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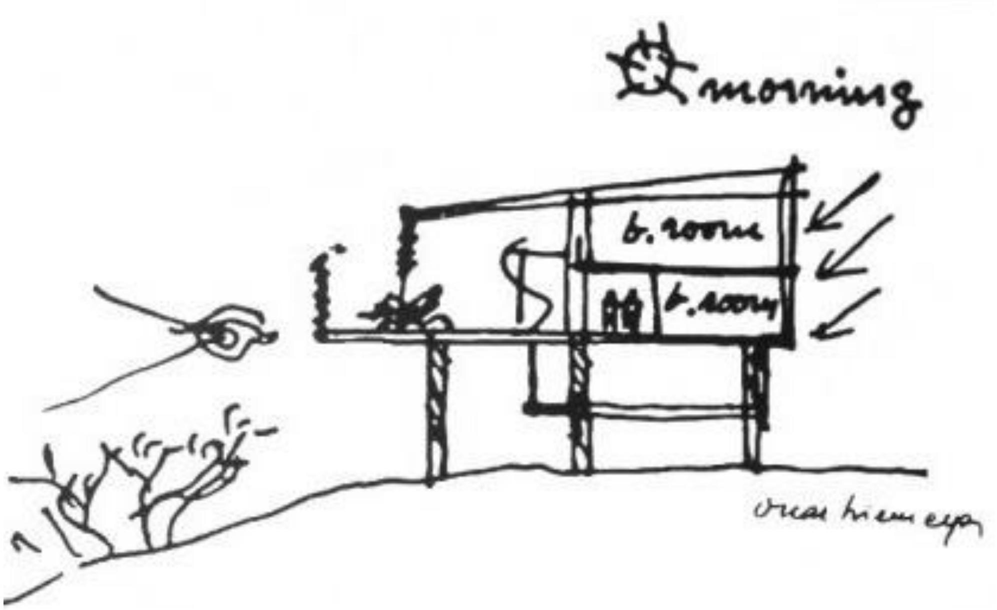
[1] Os arquitetos modernos brasileiros conquistam a posição de dominantes graças a vários movimentos que comprovam a sua superioridade em face dos competidores acadêmicos e neocoloniais nas duas extremidades do campo: a popular e a erudita. A eliminação de ornatos, a estrutura aparente, a planta 'livre', a ideia de protótipo e a possibilidade de reprodução industrial, muito mais que opções formais, eram apresentadas como justificativas éticas do movimento moderno. Não só as casas do rico e do pobre seriam igualmente despojadas, como haveria a possibilidade de, com esse despojamento, produzir casas operárias em larga escala.

Figure 3: Niemeyer’s Ouro Preto Grand Hotel design
(http://www.vitruvius.com.br/revistas/read/arquiteturismo/09.100/5633)



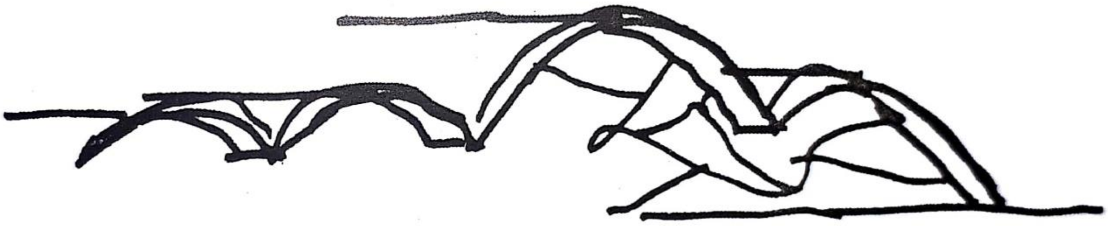
The selection of Niemeyer’s Ouro Preto Grand Hotel (Figure 3) design over a neo-colonial one marks the moment when modernists first succeed in asserting the Movement’s symbols. The event successfully established a new heritage stance, according to which new buildings in historic places can and should be built in the modernist style.

The modernist movement would reach its peak with the construction of Brasilia in 1960. The capital city, which will be discussed at a later chapter, was designed entirely within the directives established by the International Congresses of Modern Architecture (CIAM - Congrès International d’Architecture Moderne) and is home to one of the greatest collections of modernist constructions.

2.1.1 Preservation

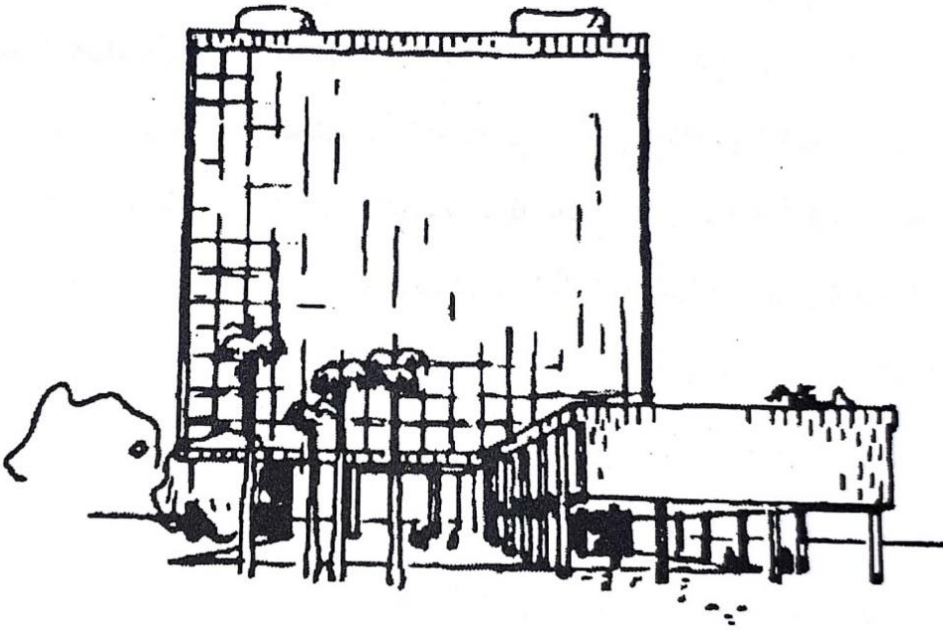
The preservation and conservation fields in Brazil were still being developed. The Artistic and Historical Heritage National Service (SPHAN) was created in 1937 by Gustavo Capanema, former Minister of Education, and Mario de Andrade, a modernist architect, in order to ‘promote, nationally and permanently, the protection, conservation, enrichment and information of historical and artistic national heritage’ (PRESIDÊNCIA DA REPÚBLICA, 1937). Furthermore, unlike European and North American legislatures, Brazilian regulation did not require temporal distance between a building's construction and its declaration as a historical monument.

Figure 4: The São Francisco de Assis Church in Belo Horizonte (NIEMEYER, 1978)



At this time, many modernist architects worked within SPHAN, writing legislative texts, formulating guidelines and overall management. The task of acknowledging and protecting that which could be considered part of the national cultural identity fell to architects such as Lucio Costa, Rodrigo Melo Franco de Andrade, Paulo Santos, José de Souza Reis, Renato Soeiro and Alcides da Rocha Miranda. According to Silva (2012), not only were they responsible for encouraging a preoccupation with national heritage, the proximity of the modernist movement to the SPHAN made it possible to determine and preserve that which should qualify as national monuments.

Figure 5: Education and Public Health Ministry in Rio de Janeiro (COSTA, 2002)



The São Francisco de Assis Church (Figure 4) and the MESP (Education and Public Health Ministry) (Figure 5) building were the first modernist constructions to be registered as National Cultural Heritage. The São Francisco de Assis Church was registered in 1947, four years after its inauguration, and the MESP building was registered in 1948 three years after its inauguration. Although newly finished, these works already constituted the creation of a national image, and therefore were thought apt to be considered national heritage.

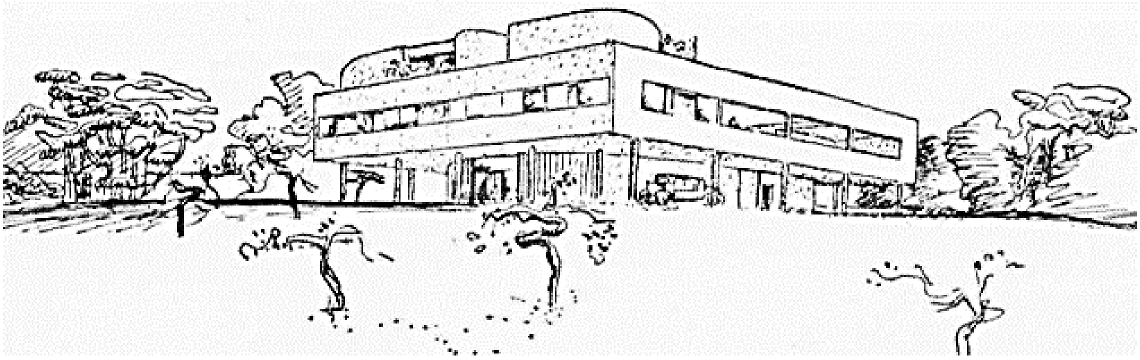
National innovation and heritage preservation walked hand in hand. While other countries would nurture rivalry between heritage and modernist protagonists, in Brazil, heritage curators and modernist precursors were one and the same (VIANNA; QUEIROZ, 2004). National modernist monuments did not receive symbolic value afterwards, as was the case of historic monuments, but simultaneously, or a little time after their construction. Nevertheless, it should be noted that despite the importance of these monuments, the lack of temporal distance between Modernist production and its registration as national heritage, has had severe consequences due to the advanced deterioration of reinforced concrete (SILVA, 2012).

Figure 6: Robie House (https://openhousechicago.org/sites/site/frederick-c-robie-house/)

Outside Brazil, the first movements for modernist architecture preservation occurred during the 1950’s in protest against the demolition of Frank Lloyd Wright’s *Robie House* and Le Corbusier’s *Villa Savoye*. Built between 1908 and 1909 in Chicago, *Robie* House (Figure 6) is considered the purest example of Wright’s Prairie Houses. Property of the Chicago Theological Seminary in 1941, it was due to be demolished in order to expand the Seminary's lodgings. With the outbreak of World War II, plans to demolish were put on hold until 1957. However, when the demolition was again announced, a series of international protests, the actions of two Chicago University fraternities, and a visit from Frank Lloyd Wright in person managed to hinder the process and preserve the construction. (PADUA, 2013)

During that time, the *Villa Savoye* (Figure 7), built by Le Corbusier in Poissy, France, between 1928 and 1931, was also at risk of being demolished. Considered a benchmark for modernist architecture, the Villa is known for most succinctly embodying all of Le Corbusier's 'Five Points of a New Architecture': the *pilotis* or replacement of supporting walls by a grid of reinforced concrete columns; the roof gardens; the open floorplan; the separation of cladding and structure, leaving the facades free from structural constraints; and the ribbon windows.

Figure 7: Villa Savoye sketch (BOESIGER, 1971)



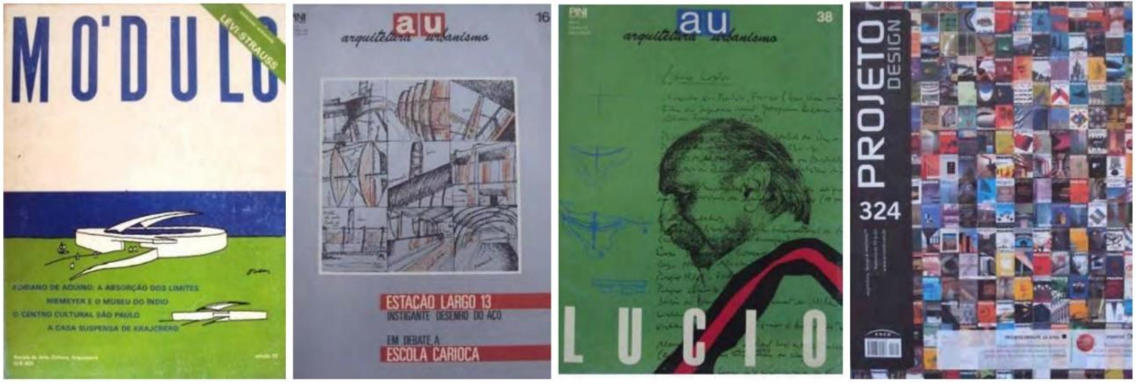
In 1959, the building was bought by the town of Poissy, who intended to demolish it in order to build a school. It was Le Corbusier himself, warned of the danger by the former owners, the Savoye family, who took actions to prevent the demolition. Even though French legislation, at the time, did not permit the protection of buildings whose authors were still alive, he appealed to French nationalism by assigning the Villa an important role in the French Modernist Movement. With the support of the society and the Minister for Culture, André Malraux, he was successful.

From 1960 onwards, Modernist Architecture icons were found to be in a state of rapid decay, jeopardising Modernist principles. The international Modernist

Movement thus began its first campaigns in order to save such principles and modernist architects began using all available means to preserve this new national and international heritage. However, international debate surrounding modernist heritage began gaining strength as recently as the late 1980's with the Convention Concerning the Protection of the World Cultural and Natural Heritage in Paris in 1985 and the founding of the International committee for documentation and conservation of buildings, sites and neighbourhoods of the modern movement (DOCOMOMO) in the Netherlands in 1988. Thus, when the international threat to modernist architecture intensified, so did preservation campaigns. Selection, custody and inventory programmes were developed, which instigated a number of debates concerning preservation criteria. (CARVALHO, 2005)

In Brazil, the 1980's marked a new phase for heritage preservation. The end of the military regime and the return of democracy enabled the return of the *Módulo* magazine and the emergence of the *Projeto Design* and the *Arquitetura e Urbanismo* magazines, all of which played important roles in the promotion and appreciation of modernist architecture (Figure 8) with special issues on modernist architects and dedicated sections on modernist architecture. (ROCHA, 2011)

Figure 8: From left to right: Módulo magazine cover (1982); AU magazine cover (1988); AU magazine cover (1991) and Projeto Design magazine cover (2007). (ROCHA, 2011)



This second phase for heritage preservation was no longer about guaranteeing the preservation of buildings that were threatened with destruction, but the recognition of the initial milestones of Brazilian Modernist Architecture.

Internationally, the early 90’s brought about an increase in debates concerning modernist architecture preservation which, in spite of political, economic and utilitarian aspects, have recognised heritage value and must be conveyed to future generations. In 1991, the Council of Europe published the Recommendation No. R (91) 13, which states that ‘twentieth-century architecture is an integral part of Europe’s historical heritage and that the preservation and enhancement of its most significant elements serve the same aims and principles as those of the conservation of the architectural heritage as a whole’. (COUNCIL OF EUROPE, 1991)

However, one must question if contemporary society is able to recognise and preserve so recent a history, whose material and expressionist worth has not been fully identified. We must redefine our relationship to the recent past in order to culturally transmit it to future generations. (CARVALHO, 2005)

Modernist Architecture preservation theories belong to the same theoretical universe as general restoration and preservation theories, even though the latter was developed for older constructions, built with longer lasting material. At the same time that we cannot dissociate the process of safeguarding modernist architecture from traditional historic preservation principles, their unrestricted endorsement can be problematic for the subject’s survival. The new design conceptions, introduced by using new materials, construction techniques and project solutions, would lead to new challenges and differentiated solutions. However, the basic principles of conservation and restoration should be always considered when making decisions (SILVA, 2012). Heritage intervention must be, first and foremost, architectural decisions which involve artistic and aesthetic criteria and historic value. Every action is characterised by the same responsibility and challenges of conceptual design. (SILVA, 2017)

In 2001, the United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Centre, the International Council of Monuments and Sites (ICOMOS) and the DOCOMOMO launched a programme to identify, document and promote 19th and 20th century built heritage. Its aim is to establish a paradigm about the importance of such heritage, its preservation and resolve the central issues involving identification and valuation. Even so, through the years, society has lost a variety of modern architecture examples, and even their records. City growth results in a sort of construction natural selection, and the problem is that the importance of many modernist buildings is not recognised by the public in general. Many buildings of the time are in precarious condition due to having been abandoned or having lost their modernist qualities. (SILVA, 2012)

However, the very act of conserving modernist construction may be considered a contradiction in terms and against the very principles which gave birth to the Modernist Movement. Italian futurists, such as Sant'Elia (apud LIMA, 2012) argued that people would outlast modern homes. Modernist architecture should be, above all, an expression of its time, endowed with flexibility and the capability to change and adapt to the demands of contemporary life. Nevertheless, with the acquired temporal distance, modernist architecture is no longer connected only to values imposed by its author, but is seen as a representation of the ideals, world visions, social and artistic practices of an era, and so, acquires patrimonial value.

But how should we determine modern heritage's worth? Lima (2017) suggests that Riegl's values[2] are as relevant for modernist constructions as they are for ancient ones. However, for the former, historic, dynamic and relative values must be weighed and considered relatively to their importance, for historic value does not imply complete and absolute value. For modernist construction, it is possible for one value to prevail over others and values such as use and art tend to predominate over remembrance. Use is considered one of the most important current preservation demands, without which construction is condemned to be abandoned and degraded. (LIMA, 2017)

Modernist construction represents a series of new material, technical and theoretical challenges to conservation disciplines: rapid function obsolescence, making it difficult to find and introduce new uses; misused novel materials, for lack of long-term studies on performance, construction and detailing flaws; infrastructure replacement and adaptation problems; maintenance deficiency;

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[2] Values that Riegl ascribes to monuments to determine their value, which include the Age Value, the Historical Value, the Deliberate Commemorative Value, the Use Value and the Newness Value (RIEGL, 1982).

patina use; residential building complexes which are not able to keep up with society changes, such as ageing, enrichment or impoverishment; and landmarking. (MOREIRA, 2010)

Today, modern built heritage suffers from the consequences of this rapid change. Design conception predominates over execution, diminishing the importance of constructed matter. The fragility and vulnerability of construction materials, along with limited knowledge of component degradation processes, may impair maintenance procedures and lead to safety risks. Installation obsolescence, sustainable performance demands and evolving regulations have become constant daily challenges (SILVA, 2017).

The question that remains is how to identify, document, promote and preserve Modernist architecture. It is the main challenge facing all national and international debate. For the sake of this research, we will focus on intervention, conservation, restoration and maintenance techniques in order to demonstrate how modern technology can assist with the respective decision-making process.

2.1.2 Conservation and Maintenance Guidelines

It is not within the scope of this research to investigate or discuss the selection criteria for what should and should not be protected. Nor is this research intended as a plea for the preservation of its use case. Our goal is merely to offer a more efficient conservation and maintenance strategy for the already decaying modernist heritage. However, we must first understand the concepts of *conservation*, *preservation*, *maintenance* and *restoration* according to the principal guiding documents.

With regard to modernist architectural heritage, conservation is the most comprehensive term, encompassing all actions and mechanisms intended at preventing, protecting and retarding the deterioration process and the loss of value. On conservation, the predominant guiding document for preservation practices today, the Venice Charter of 1964 (ICOMOS, 1964) dictates:

> Article 2. The conservation and restoration of monuments must have recourse to all the sciences and techniques which can contribute to the study and safeguarding of the architectural heritage

> Article 3. The intention in conserving and restoring monuments is to safeguard them no less as works of art than as historical evidence
>
> Article 4. It is essential to the conservation of monuments that they be maintained on a permanent basis

The charter was established at a time when most of the world was dedicated to repairing the profound consequences of World War II. It introduced the concepts of minimal intervention and distinguishability and examined issues such as the importance of treating restoration as a critical-historical act, the necessity of taking into consideration the location of monuments, the necessity of conserving the accretions of different times, the need to research the monument previously to any action, and to document each intervention. The charter further defines restoration:

> Article 9. The process of restoration is a highly specialized operation. Its aim is to preserve and reveal the aesthetic and historic value of the monument and is based on respect for original material and authentic documents. It must stop at the point where conjecture begins, and in this case moreover any extra work which is indispensable must be distinct from the architectural composition and must bear a contemporary stamp. The restoration in any case must be preceded and followed by an archaeological and historical study of the monument. (ICOMOS, 1964)

However, it was only during the 1980’s when international organisations begin discussing the protection and preservation of Modernist Monuments, culminating with the Council of Europe in 1991. Section III of the Council of Europe’s 1991 Recommendation (COUNCIL OF EUROPE, 1991) sets forth guidelines for management and conservation of twentieth-century heritage. It states that authorities must encourage the most appropriate use for each asset and, when necessary, bolster new uses which take into account the needs of daily life, in order to avoid the abandonment and consequential decay of buildings.

In order to prevent deterioration by atmospheric pollution and the ageing of materials, the guidance supports the maintenance and restoration of heritage by promoting practical, theoretical and scientific studies into construction methods, maintenance, restoration, and twentieth-century materials, respecting the ‘same fundamental principles as are applied to other elements of the architectural heritage in planning programmes of maintenance and restoration of these structures’, creating a complete record of conservation observations and actions and setting up appropriate information systems and architectural records, either nationally or regionally, so that the building's history remains recorded and its future maintenance ensured.

The Nara Document on Authenticity (ICOMOS, 1964) was aimed at developing and expanding the Venice Charter due to the expansion of the cultural heritage concept and its importance to the modern world. It further develops the concept of conservation:

> Conservation: all efforts designed to understand cultural heritage, know its history and meaning, ensure its material safeguard and, as required, its presentation, restoration and enhancement. (Cultural heritage is understood to include monuments, groups of buildings and sites of cultural value as defined in article one of the World Heritage Convention).

The 1995 ICOMOS Seminar on 20th Century Heritage in Helsinki reiterated that established conservation principles represent a valid basis for safeguarding and conserving recent heritage and further emphasised the imperative of systematically documenting 20th century heritage in all its dimensions and in relation to its context, taking into account the potential offered by new recording methods. Documentation which today has the potential to be revolutionised by methods such as laser scanning, photogrammetry and BIM-assisted facilities management.

The 1996 edition in Mexico City went further to indicate that:

> 2.3.1 Preservation must occur in a dynamic sense in order to respect the values indicated in each work and to make possible its enjoyment and use in the future. These interventions must be controlled by technical instances which make possible the respect and development of the works.
>
> 2.3.2 New techniques must be taken into account, along with the accelerated proliferation of new materials or the disappearance of others, with the purpose of discerning possibilities of change and modalities of intervention. To be pointed out are both, the positive examples which enrich the intervened objects and the negative ones which destroy or deform important values. In this task, collaboration with other technical disciplines is opportune and fundamental, always from the vantage point of preserving authenticity.

As stated, intervention must be controlled by technical instances and new techniques must be taken into account. It is also necessary to consider the constantly evolving modalities of intervention brought by the disappearance of one material and proliferation of another.

According to the Burra Charter (AUSTRALIA ICOMOS, 1999),

> Conservation may, according to circumstance, include the processes of: retention or reintroduction of a use; retention of associations and meanings; maintenance, preservation, restoration, reconstruction, adaptation and interpretation; and will commonly include a combination of more than one of these. (p. 6)

Furthermore, ‘maintenance is fundamental to conservation’ and should be undertaken wherever necessary to maintain the cultural significance of a site, area, land, landscape, building or group of buildings. Work should be preceded by an analysis of documentary, physical and oral evidence and should be executed with the appropriate knowledge, discipline and skills. Lastly, conservation records must be kept and made publicly available whenever possible or culturally appropriate.

Restoration, on the other hand, ‘is appropriate only if there is sufficient evidence of an earlier state of the component, fixture, content or object’ (AUSTRALIA ICOMOS, 1999). The concept dates back Cesare Brandi’s Theory of Restoration as ‘the moment in which an art work is recognised for its physical consistency and its aesthetic and historical double polarity so as to transmit it to the future[3]‘. (BRANDI, 1963) Furthermore, ‘restoration must strive to re-establish the potential unity of the art work, as long as it is possible to do so without committing an artistic or historic falsehood, nor cancelling any trace of its passage through time[4]‘.

The 1972 *Carta Italiana del Restauro* further states:

> Protection is understood as any conservative measure which does not interfere directly with the artwork; Restoration is understood as any interference directed at efficiently maintaining an art work, facilitating its understanding or fully transmitting it to the future.[5] (MINISTERIO DELLA PUBBLICA ISTRUZIONE, 1972)

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[3] il momento metodologico del riconoscimento dell'opera d'arte, nella sua consistenza fisica e nella sua duplice polarità estetica e storica, in vista della sua trasmissione al future. (p. 6)

[4] il restauro deve mirare al ristabilimento della unità potenziale dell'opera d'arte, purché ciò sia possibile senza commettere un falso artistico o un falso storico, e senza cancellare ogni traccia del passaggio dell'opera d'arte nel tempo (p. 8)

[5] S’intende per salvaguardia qualsiasi provvedimento conservativo che non implichi l’intervento direto sull’opera: i’intende per restauro qualsiasi intervento volto a mantenere in efficienza, a facilitar ela lettura e a trasmettere integralmente al futuro le opere e gli oggetti definiti

However, for the sake of the present research, the definitions adopted are Dongming Lu's and Yunhe Pan's, who define conservation of cultural heritages as 'creating a safe and appropriate environment and taking positive measures to increase their life spans and avoid deterioration and damage', 'restoration aims to artificially restore damaged cultural heritages and improve their conservation status and prolong their life' (LU; PAN, 2010 p. 89). Whichever the solution, it is clear that technology has become paramount to conservation, be it for maintenance or restoration.

Cultural heritage investigation and application can benefit from digital technology using two main methods to aid in traditional investigation methods, improving efficiency and solving complex problems or by providing completely new methods of investigation, based on cultural heritage digital information. Either way, 'it helps to acquire information related to the environment, mapping, status and deterioration of cultural heritage and manages the investigation information through databases, thus providing detailed information for developing a conservation plan' (LU; PAN, 2010 p. 90). In subsequent chapters, we will explore the benefits this research will bring to the conservation, maintenance and restoration of architectural heritage.

2.2 Brasília

In 2017, Brasilia commemorated 30 years as a UNESCO World Heritage site, the same year in which the Brazilian National Institute for historical and artistic heritage (IPHAN) commemorated 80 years of existence, both pioneers in their own right. The IPHAN (1937), representing the urgent nationalism of the Vargas Era, which would come to landmark monuments not only for their memory and historical meaning, but their sense of national identity and sovereignty. National pride was reconstructed with new national potential as well as the people's history and public spirit. (VIANNA, 2017)

Later, during the Juscelino Kubitschek government, Brasilia was constructed at the height of this civic spirit, representing all the emotional charge of modernisation and nationalism. As the President himself said:

> In the world there are some artificial cities, that is, cities that were not developed by social-political imposition, but created by the initiative of kings or rulers. Their construction dragged on through the years and, even though much time has passed, some have not yet been concluded. On the other hand, none of them possess in their history – a history of heroism, audacity, determination and the epic pioneering spirit which represented the construction of the new capital, giving it a badge of unprecedented importance when compared to its counterparts. The new Capital, aside from its architectural grandeur, allowed the conquest of two-thirds of our territory, which previously were seen as disheartened empty spaces.[6] (KUBITSCHEK, 2000 p. 10-11)

Representing the evolution of modern architecture and Urbanism, the city was 'born' with historical value, while, at the same time, changed history with the global arrival of modernity. The designed centre of the capital, called *Plano Piloto*, can be described as an urbanistic synthesis of different cities: a representative monumental city; a highway city, structured through a regular and hierarchic grid; a park city, with large green spaces; and a central city, from which would spring a number of new satellites. (LIMA, 2012)

The Capital's project was not about designing a city, but conceiving a capital within the open horizons of a savannah landscape. To this end, the winner of the 1957 competition for the city's design, Lucio Costa, worked with its historical references as well as a clear application of modernist architectural and urbanist principles, represented by the distinct subdivision of the urban fabric. The baroque perspectives, the monumental embankments, the Brazilian colonial gregariousness, the ceremonial acropolis, the linear city, the garden city, all found a position within his design. The competition's jury were right, the design had 'character', rescuing in many ways a pre-modern organisation, such as the continuation of the urban fabric in a global scale. (HOLANDA, 2010)

The Capital's original design sprang from two axes in a clear configuration of spatial identification and urban accessibility (Figure 9). As Costa (1995) himself

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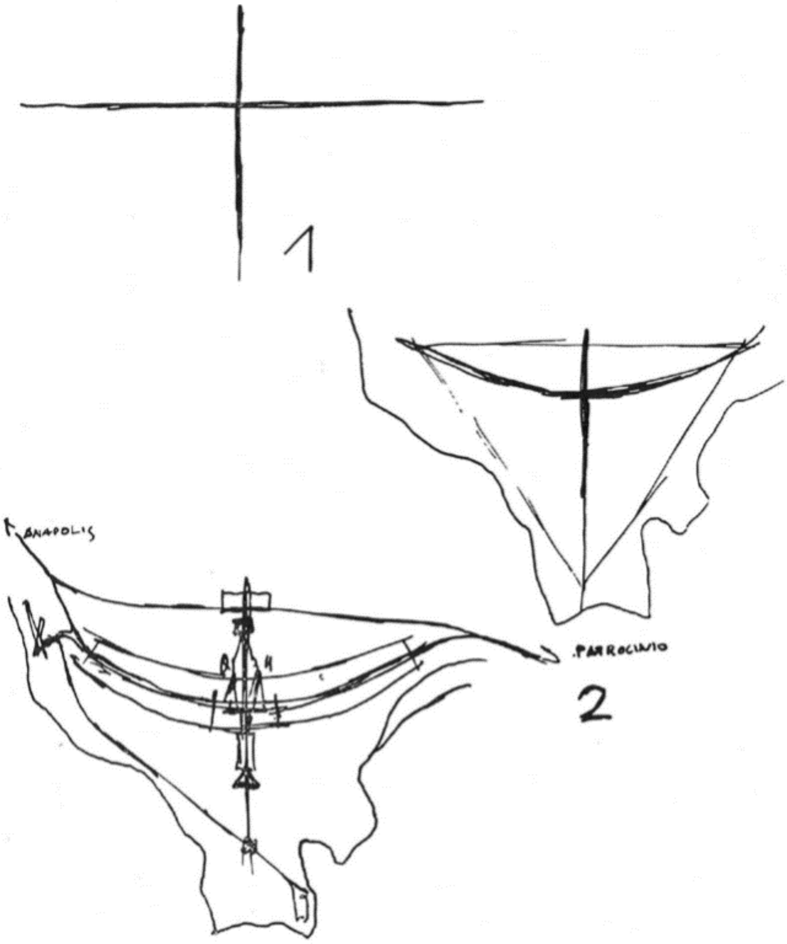
[6] No mundo existem algumas cidades artificiais, isto é, não nascidas por imposições sociopolíticas, mas erigidas por iniciativa de reis ou de governantes. A construção de todas elas arrastou-se através dos anos, e algumas, apesar do tempo passado, ainda não estão de todo concluídas. Por outro lado, nenhuma delas possui uma história própria -uma história de heroísmo, audácia, determinação e espírito de pioneirismo épico, que representou sua construção, exibe uma insígnia que lhe empresta importância ímpar, quando posta em comparação com suas congéneres. A nova Capital, descontada sua grandiosidade arquitetônica, permitiu que dois terços do nosso território — que eram desalentadores 'espaços vazios' — fossem conquistados

put it: ‘it sprang from the initial gesture of someone designating a place and taking possession of it: a cross formed by two bars intersecting at right angles’ (COSTA, 1995). The administrative and government functions were allocated adjacent to the monumental axis and the intersecting axis organised the city’s housing blocks. The residential fabric is continuous, interrupted only by the city’s urban centre – *urbis* – and its administrative space – *civitas*.

Figure 9: Lucio Costa’s first sketches for Brasilia (COSTA, 1995)



Many changes were made to the original project throughout the city’s construction, in which the ‘reality was larger than the dream’ (LIMA, 2017). Hence, Holanda (2010) argues that the design now represents in some ways a Utopia and in others, a myth. In what ways does the city’s architecture transcend the limits of space and time? Does it innovate? Advance? Do its values hold true today? And in what ways do its initial representations reveal themselves as mythical?

Gorovitz (2014) argues that the Utopia still lives through the promise of a more humane way of living, however mutilated and overturned the original project, which was not able to overcome its contradictions. The impossibility of turning the Utopia into reality is what makes the myth.

The city represents the world not as it is, but as how it should be, fruit not of a society's realisations but its aspirations. The design's innovation is just that. It is at the same time utopian – nothing similar was ever done before or will be done afterwards – and mythological.

2.2.1 Urban Scales

The city was designed according to four fundamental configurational architypes, which constitute the *heart* of the metropolis, called *scales*. The scales are urban configurations with specific attributes relating to building types and open space structure. However, they may not precisely correspond to specific city sections, they can also be incorporated within the other scales. (HOLANDA; TENORIO, 2014)

> Brasilia's urban conception translates itself into four distinct scales: monumental, residential, gregarious and bucolic. The monumental scale's presence – not ostentatious but as a palpable expression of that which is worthy and meaningful – bestowed the new-born city with an inescapable brand as active country capital. The residential scale – with its innovative *superblock* proposal, its urban serenity due to its uniform six-story high buildings, its open first floor accessible to all through the use of *pilotis* and the predominance of nature – brought with it the embryo of a new manner of living, unique to Brasilia and completely different from all other Brazilian cities. The gregarious scale, contemplated for the city`s centre – till this day sparsely occupied – was intended as a densely utilized urban space, conducive to human interaction. The extensive green spaces, to be densely forested or retain its native vegetation, directly adjacent to built-up areas, defines the bucolic scale.[7] (COSTA, 1986)

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[7] A concepção urbana de Brasília se traduz em quatro escalas distintas: a monumental, a residencial, a gregária e a bucólica. A presença da escala monumental — 'não no sentido da ostentação, mas no sentido da expressão palpável, por assim dizer, consciente daquilo que vale e significa' — conferiu à cidade nascente, desde seus primórdios, a marca inelutável de efetiva capital do país. A escala residencial, com a proposta inovadora da Superquadra, a serenidade urbana assegurada pelo gabarito uniforme de seis pavimentos, o chão livre e accessível a todos através do uso generalizado dos pilotis e o franco predomínio do verde, trouxe consigo o embrião de uma nova maneira de viver, própria de Brasília e inteiramente diversa da das demais cidades brasileiras. A escala gregária, prevista para o centro da cidade — até hoje ainda em grande parte desocupado — teve a intenção de criar um espaço urbano mais densamente utilizado e propício ao encontro. As extensas áreas livres, a serem

Each scale is defined by exclusive characteristics, with building types and urban elements according to designated use. The Residential Scale, comprising not only residential buildings, but also commerce, schools and churches, introduced a new manner of living. The Monumental Scale is what the city is known for and contains the Ministries, the Three Powers Square, the National Congress (Figure 10) and other administrative and governmental constructions. The Gregarious Scale, at the city centre, houses service and commercial centres and provides a civic meeting space. Lastly, the Bucolic Scale is defined by the extensive open spaces composed of native vegetation or densely forested. (OLIVEIRA, 2012)

Figure 10: Brazilian National Congress. (private collection)

Each scale is distinguished by the peculiar manner in which its parts are plastically organised. Costa’s (1995) main purpose in his design was to promote citizenship and therefore each scale serves to distinguish the collective from the private, which his design then sews back together to constitute a harmonic whole. In this manner, proportion is used to counterbalance the everyday scale from the others in such a way that none superimposes itself over the others. Thus, the dimensions of the Neighbourhood Areas, composed of four superblocks framed by forested strips, constitute plastic entities that ‘organize the urban fabric

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densamente arborizadas ou guardando a cobertura vegetal nativa, diretamente contígua a áreas edificadas, marcam a presença da escala bucólica.

through the correspondence of the parts to the whole' (GOROVITZ, 2014 p. 137). Furthermore, the Residential Axis was sized proportionally to the Monumental Axis as a fundamental part of the urban composition, giving the residential sector a certain monumental feature.

Figure 11: Brasilia's four scales (HOLANDA; TENORIO, 2014)

The Monumental Scale is arranged throughout the entire monumental axis, as shown in dark blue on Figure 11. However, the most memorable is located east of the bus station platform: the cultural sectors, the Ministry Boulevard and the Three Powers Square, all located atop artificial embankments, the Three Powers Square being slightly lower than the rest. Together, they make up the city's civic centre and house the most iconic constructions, whose volumes contribute to the ensemble's plastic diversity: The National Theatre, the National Museum, the National Library, the Ministry of Justice, the Itamaraty Palace, the Metropolitan Cathedral and the National Congress. However, the manner in which the constructions interact with the open spaces is even more particular: the former become the means by which the latter are defined. (HOLANDA, 2010)

The large open spaces; the predominance of length over width; the highlighting of the most important constructions through artificial embankments; the detached buildings, individually readable throughout the landscape; the transitions between interior and exterior, conceived in myriad ways, such as stairs, ramps, tunnels and walkways; the exclusive presence of those who work there; these are all characteristics which encompass the grandeur of the Monumental Axis.

However, the promise of what could have been still remains. In his design, Costa (1995) proposed an even richer space, with low buildings which would connect the ministries and house complementary services, such as restaurants, bars, newspaper stands, and lottery stalls. These spaces would add a certain informality, livening up the otherwise desolate in-between spaces at times other than when people are arriving at or leaving work. The space would be more instrumentally lived from within, than expressly enjoyed from without. However, local government persists in repressing the initiative, weakening 'the role played by the monumental spaces of the capital in people's minds, by making them exclusively symbolic spaces' (HOLANDA; TENORIO, 2014 p. 141)

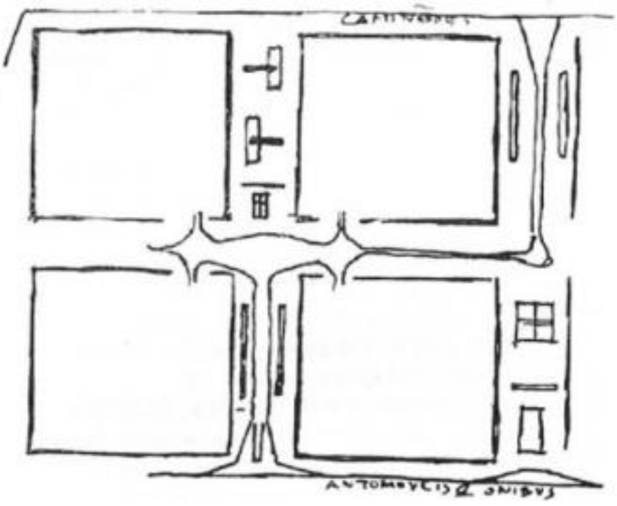
As with the Monumental Scale, the Gregarious Scale's predominantly formal conception is permeated with public spaces. Nevertheless, its physical discontinuity and use segregation have turned it into an archipelago. Commercial, banking, hospitality and hospital sectors are isolated from each other and within themselves and spatial discontinuity hinders public appropriation.

> Lucio Costa envisioned this as a busy place, a blend of Piccadilly Circus, Times Square and the Champs Élysées. The result was nothing like it. Access is difficult and unsafe; there is neither shade nor cosy squares; open spaces are dominated by vehicles and dimly lit. However, thousands of people pass by every day. (HOLANDA; TENORIO, 2014 p. 141)

Here, again, the Utopia and the myth of the original project presents itself. Would the combination of uses and the construction of the building which would join the northern and southern amusement sectors be enough to give the space continuity? Notwithstanding the discrepancies between concept and reality, the gregarious scale has thrived by permeating other scales. City life, which was designed to inhabit the intersection of the axis, now flows through every local interaction.

As mentioned previously, the residential axis provides a certain monumental way of living and its plastic conception aims to promote the citizen-citizenship relation. The design of the Residential Scale proposed two building types: the superblocks and the individual houses, and a group of four superblocks to make up a Neighbourhood Area, as seen in Figure 12.

Figure 12: Neighbourhood Area (COSTA, 1995)

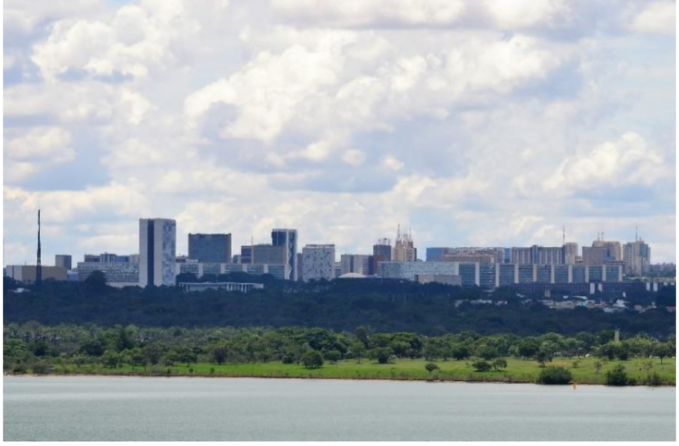


Its fundamental principles were: a green belt around a cluster of buildings; concentration of vehicle circulation within a small central area, with the remaining areas dedicated to gardens and walkways; only one vehicle entrance; a maximum six-storey limit; open first floors with *pilotis*; and schools built far from the superblock's entrance, where access would be mainly pedestrian. However, the lack of local urban control during the city's construction produced unwanted barriers, such as: residential buildings elevated from the ground; living-fences, which illicitly turned public spaces into private ones; exaggerated use of garage entrances; and contrasting ground heights, which hinder pedestrian routes and visually impair the landscape.

The greatest contradiction, however, is the limited construction types, which can only shelter high-income families. 'History has proved this repertoire to be limited: neither now nor then have they met the demand for the social diversity of the Brazilian city' (HOLANDA; TENORIO, 2014 p.142).

The transition between urban and rural is represented by the Bucolic Scale, made up of low density areas which surround the *Plano Piloto*, short buildings spaced far apart – with a few exceptions – and long stretches of preserved natural landscape. However, the spaces should have been more clearly defined. The uninhabited areas become neglected, a breeding ground for criminality, and the empty spaces exponentially increase the cost of urban infrastructure (Figure 13).

Figure 13: Uninhabited spaces between the monumental scale and the Paranoá Lake (private collection)



The Paranoá Lake is a significant component of the Bucolic Scale. It was meant to be accessible to all, distinct from the traditional image of Brazilian cities, where bodies of water usually have constructions and barriers all around. According to Costa (1995), clubhouses, restaurants, spas and fishing groups were meant to be the exception, but unfortunately became the rule, as they occupy most of the lake's western shore. Furthermore, the relocation of the design's individual houses to the lake's eastern shore, in order to bring the city closer to the lake, effectively occupied most of the eastern shore. The remaining spaces, on either shore, are either poorly furnished or financially inaccessible.

Nevertheless, here again is a scale which permeates the others. Green spaces are ever present, be it in the Monumental, Gregarious or Residential scales.

2.2.2 Architecture

According to Rossetti (2012), 'to think about Brasilia is to think about architecture'. Built in 'the middle of nowhere', the Capital gained life, image and symbols through its architecture. The city's architecture, to this day, impresses all who visit it and the presence of its main architect, Oscar Niemeyer, throughout its spaces and landscapes remains mundane and at the same time exceptional, due to the plastic, formal and symbolic control of his designs (Figure 14). Not only a city, 'Brasilia became a complex human, technical, social, cultural and political artefact, precisely because on an exceptional urban framework which hosts and informs its architecture'.

Figure 14: *Duque de Caxias* Monument in front of the Military Headquarters (private collection)

Brasilia’s architecture is composed mainly of a post-50’s production, along with some brutalist aspects of the 60’s and 70’s. According to modernist principles, the city’s buildings must be considered in relation to the city spaces, instead of each being isolated within its plot. Their structure must be readable, their construction materials expressed and their aesthetic evocative of an industrial production. All of which implies in interdependence between structure and cladding, i.e. open floorplans where the structural elements allow walls and windows to be built and modified as needed (Figure 15). Thus, Brazilian modernist architectural language would incorporate hollow elements, glass tessellations, *granilite* (a mixture of marble, granite, sand, cement and water), tiling and ceramic floors (ROSSETTI, 2012).

Figure 15: Supreme Federal Court (*Superior Tribunal Federal*) – STF (private collection)

Within a national scope, the accomplishment – design and construction of Brasilia – expands and strengthens the architect’s range of activities, going from working exclusively in offices to integrating the AEC (architecture, engineering and construction) industry and enabling the exploration of a new architectural language and insertion within new architectural programmes, such as motorways, metro stations, airports and hydroelectric power plants. This process marked a turning point in architectural history with the introduction of new issues to architectural debate.

Figure 16: Nossa Senhora de Fátima Church (private collection)

This historical process produced a great variety of constructions with an even greater variety of functions, from common to extraordinary. Aside from palaces, tribunals, ministries, embassies and the like, there was massive manufacture of hospitals, schools, theatres, clubs, residential buildings and churches (Figure 16), much of it as representative to the modernist movement as any palace, tribunal or embassy.

2.2.3 Protection

As a clear representation of Le Corbusier's modernist ideals of separating living, working, playing and moving, the city was the first 20th century construction to be landmarked by UNESCO (1987), before even Bauhaus or Corbusian architecture. (VIANNA, 2017)

Nationally, even though officially listed as a world heritage site only in 1987, Brasilia was protected since her inception. Her modernist layout was considered valuable since the beginning, and was protected from disfigurement by the Santiago Dantas Law as early as April 13th, 1960, 8 days before the city's inauguration. It was then decreed that any change to the city's layout had to be authorised by national law. (GOMES DA SILVA; DERNTL, 2017)

In 1985, Brasilia was proposed for inclusion on the UNESCO World Heritage list. In an era when there were still no new heritage accreditation criteria, this proposal surprised even UNESCO, by suggesting that the criteria for the 'new' heritage were very much like the criteria for an 'ancient' one, which is its exceptional universal value. Furthermore, the city also complied with other UNESCO selection criteria, such as 'representing a masterpiece of human creative genius' and 'being an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates a significant stage in human history'. The former by portraying the product of a combination of creative geniuses, such as Lúcio Costa, Niemeyer, Burle Marx and Athos Bulcão, and the latter incorporating the optimal representation of the modernist period (VIANNA, 2017).

Thus, the city would integrate the lists of international cultural heritage because of its modernist architectural and urbanist values, as stated in the ICOMOS recommendation:

> The 20th century principles of urbanism, as expressed in 1942 in the Athens Charter or in the 1946 Manière de penser l'urbanisme by Le Corbusier, have rarely been applied at the scale of capital cities. (…) The definition of an urban ideal based on the separation of functions, the incorporation of vast natural spaces and a street plan whose wide traffic lanes broke with the tradition of narrower streets, was implicit in the theoretical training of Costa and Niemeyer. However, the practical development of their own style meant that the primary functionalism of the 'International Style' would be rejected in favour of solutions better adapted to the Brazilian context. (ICOMOS, 1986)

The challenge now was how to preserve an economic and socially dynamic area without physically incapacitating it and allowing it to evolve and adapt. The answer was a new type of conservation strategy, preserving only the urban concept and a few essential constructions. The city was landmarked in an innovative manner, fixing the essential scales and the balance between them. Thus, the monumental, gregarious, residential and bucolic scales give meaning and order to Brasilia's historic heritage and conservation practices. The legislative spirit is to maintain the memory of an ideal and, at the same time, ensure the morphologic attributes that enable citizen social appropriation (LIMA, 2012).

The Capital's urban preservation does not guarantee the effective conservation of many specific buildings within its perimeter. There are no real preservation criteria for modernist exemplars that were not included in the initial preservation process. It is necessary to develop procedures and tools that contribute to the conservation of these important architectural specimens' fundamental characteristics.

Figure 17: Brasilia Metropolitan Cathedral (private collection)

Until 2007, there were only three protected individual assets in Brasilia: the President's first temporary residence during the city's construction, known as Catetinho; the Brasilia Metropolitan Cathedral (Figure 17) and the golden plate given by the Senate to Rui Barbosa for his participation at the Haia Conference in 1907. In 2007, when Niemeyer celebrated his 100th birthday, he requested that the entire Oscar Niemeyer Architecture Compound be declared national heritage. Since then, many buildings which represent the modernist ideal are going through the landmarking process. They all represent the ideals of order, balance, composition, harmony, symmetry, consistency and beauty (OLIVEIRA, 2012).

2.3 University of Brasília

The University of Brasilia (UnB) was created the same year as the city's inauguration, in 1960, at a time of intense debate within Brazilian society concerning higher education. The construction of a new university at the country's capital was therefore considered an extraordinary opportunity to reassess the obsolete structure of Brazilian universities at the time. Its design was the product of an intense collective debate between scientists, intellectuals and professors from a myriad of areas at the Brazilian Society for Science Progress (SBPC) symposium in October, 1960.

Belonging to the Bucolic Scale, the university's campus was initially designed to be constructed quite close to the Ministry for Education and the Cultural Sector. However, due to a fear of student movements too close to government facilities, it was moved a few kilometres away and is currently situated according to Figure 18.

Figure 18: UnB location (IPHAN, 2016)

The original project dictated that the university be subdivided into three organisational levels: the central institutes – Mathematics, Physics, Chemistry, Biology, Geosciences, Human Sciences, Literature and Arts – the colleges and the complementary bodies. The Central Institutes were then divided into departments, which made up the university's base units. Thus, its architecture needed to correspond to the pedagogical innovations. To this purpose, the ICC was conceived as the campus' structuring element, around which all others would be arranged: the Central Library, the Campus Restaurant, the Arts Institute, the Law College, the administrative buildings, etc. (SCHLEE, 2014).

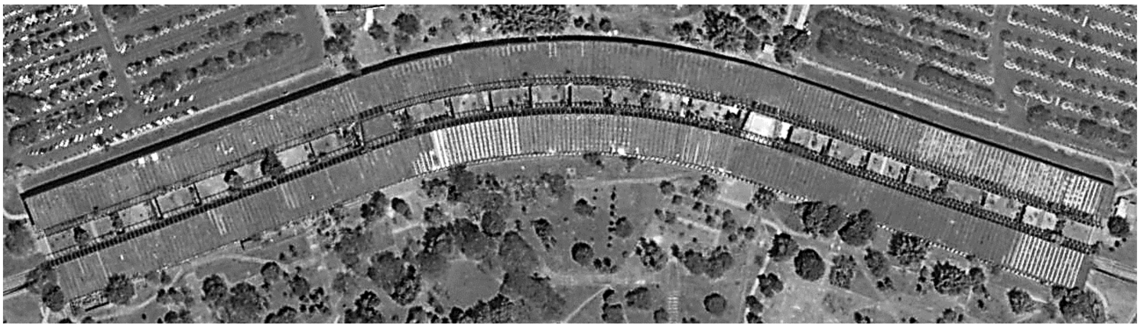
The initial campus layout draft was created in 1960 by Lúcio Costa. However, much was changed in 1962 by Oscar Niemeyer, chief of the University Centre for Planning (CEPLAN), whose aim it was to design all the university buildings within the urban principles set out by Costa and establish, guide and mentor the Architectural College. Predominant amongst these changes was the unification of the five central institutes – Mathematics, Physics, Chemistry, Biology and Geosciences – into one building, the ICC (FONSECA, 2007).

2.3.1 Central Science Institute

The ICC was constructed between 1962 and 1975, and is the first university building in Brazil to integrate several science institutes under one roof, an innovative approach where university students could have access to a number of fields even without being directly affiliated to them. This proposal would come to strengthen the integration value of the university's equally innovative pedagogical plan. Students belonging to different institutes became part of something bigger, strengthening their bond and university loyalty. Thus, the juxtaposition of educational and architectural planning and of functions and uses enabled social interaction and fostered a new conceptual paradigm. (ALBERTO, 2009)

Pre-fabrication soon became one of the university's principal motifs and most of its first buildings were designed and constructed according to this technique. Very early on, João Filgueiras Lima, a member of Niemeyer's team known as Lelé, was encouraged to integrate with the CEPLAN, a centre for industrialised construction and technology to be used by the university. At the time, pre-fabricated construction technology was believed to be the answer to the country's construction problems. Such was the university's belief that Lelé and a colleague were sent to the Soviet Union, Germany, Poland and the former Czechoslovakia to research technical and construction solutions. (ALBERTO, 2009)

Figure 19: ICC from above (Google Earth)



The ICC is composed of two symmetrical and homogeneous buildings, whose floorplan shape represents an arch in the middle with rectangular extremities (Figure 19), in the exact opposite manner of the *Plano Piloto*. The two constructions are parallel and separated by a 16-metre strip of gardens and circulation (Figure 20). The main entrances are located at either end of the arch, whose interior is marked with empty spaces, mezzanines and large cantilevered ramps. There are two secondary entrances at both extremities. The building's architecture is derived from its structure, where beams, slabs and pillars define architectural composition and form, composed of a prestressed frame system, repeated every three metres through the entire building span (BORGES, 2015).

Figure 20: circulation and gardens between the constructions (private collection)

The complex was initially designed to extend over 600 metres in length and have a 20-metre central strip, but was effectively built with a 720-metre length and a 16-metre strip. It was also meant to have a transversal occupation with each college inhabiting a section of both the eastern and western blocks, which housed laboratories and auditoriums respectively. Nonetheless, the buildings were occupied in a longitudinal manner and auditoriums became classrooms. The western block is 29.6 metres wide and houses the auditoriums.

A chosen section of the ICC will function as this study’s use case, to be evaluated through Visual Analytics and the proposed depreciation-deterioration hybrid method which will be explained further on.

3 VISUAL ANALYTICS

Visual Analytics (VA) can become a powerful tool in the hands of a facilities manager. Most O&M decisions today are made using a text-based data application, such as the Computerized Maintenance Management System (CMMS). However, due to complex interrelations between building components and systems, changing environmental factors and the variety of building components, it can be extremely difficult to determine failure root causes in CMMS. Spatial information distribution in a BIM model can greatly benefit root cause detection by facilitating simultaneous visualisation of a large amount of lifecycle data. Thus, VA combines ‘automated analysis techniques with interactive visualization for effective understanding, reasoning and decision making on the basis of very large and complex datasets’ (MOTAMEDI; HAMMAD; ASEN, 2014).

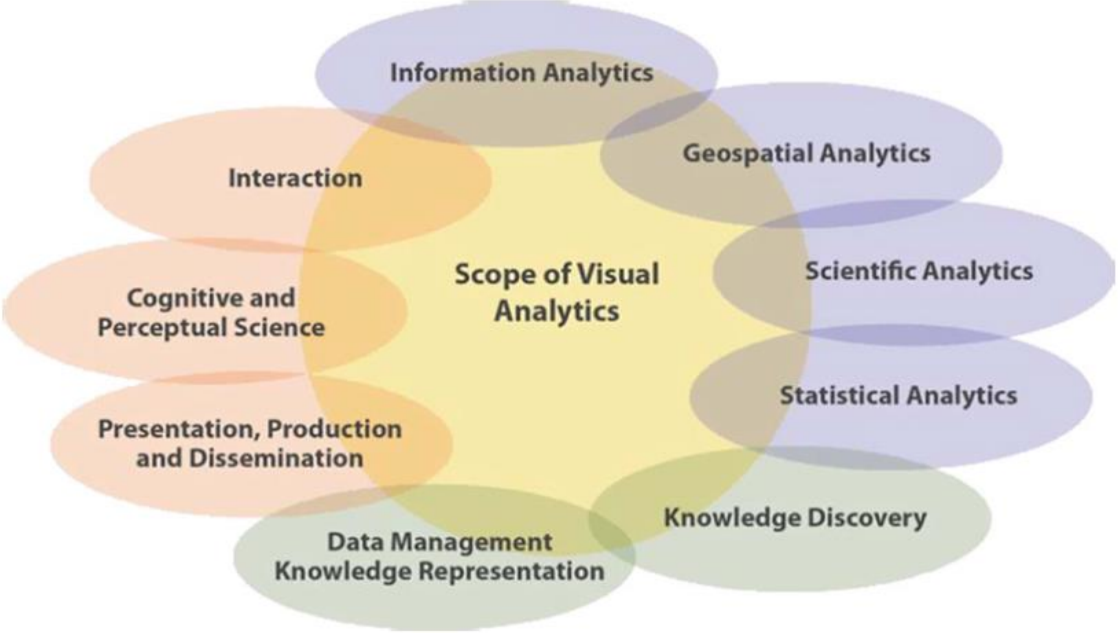
> Recording the physical characteristics of historic structures and landscapes is a cornerstone of preventive maintenance, monitoring and conservation. (MEZZINO et al., 2017)

Therefore, VA can be used to determine the main cause of a problem by analysing lifecycle knowledge and the relationship between BIM elements. It can also infer patterns and trends through the spatial and frequency distribution of present and past problems. Furthermore, it can be used to simulate resulting effects of asset relationship by visualising the chain of effects caused by a components’ status change. (MOTAMEDI; HAMMAD; ASEN, 2014)

3.1 What is VA

According to Thomas and Cook (2005), VA is the ‘science of analytical reasoning facilitated by visual interactive interfaces’. It involves the cooperation between a variety of scientific communities, such as interactive design, graphic design, information visualisation, computer science, cognitive and perceptual sciences and social sciences and undertakes challenges involving visual representations, interaction techniques, analytical reasoning and data representation (Figure 21). It is driven by the necessity to solve problems and make sound decisions through ‘innovative interactive techniques and visual representation based on cognitive, design and perceptual principles’ (CHEN et al., 2012).

Figure 21: VA sub-disciplines (KLUSE; PEURRUNG; GRACIO, 2012)



The concept is rooted within the Visualisation community and sprang from the necessity to understand the increasingly complex analytical problems of modern society and manage the ever-expanding amount of data. As the complexity of data increased, human cognitive abilities remained relatively constant. VA thus combined the ‘analysis capabilities of the computer and the visual perception and analysis capabilities of the human user’ to enable novel discoveries and insights (KLUSE; PEURRUNG; GRACIO, 2012).

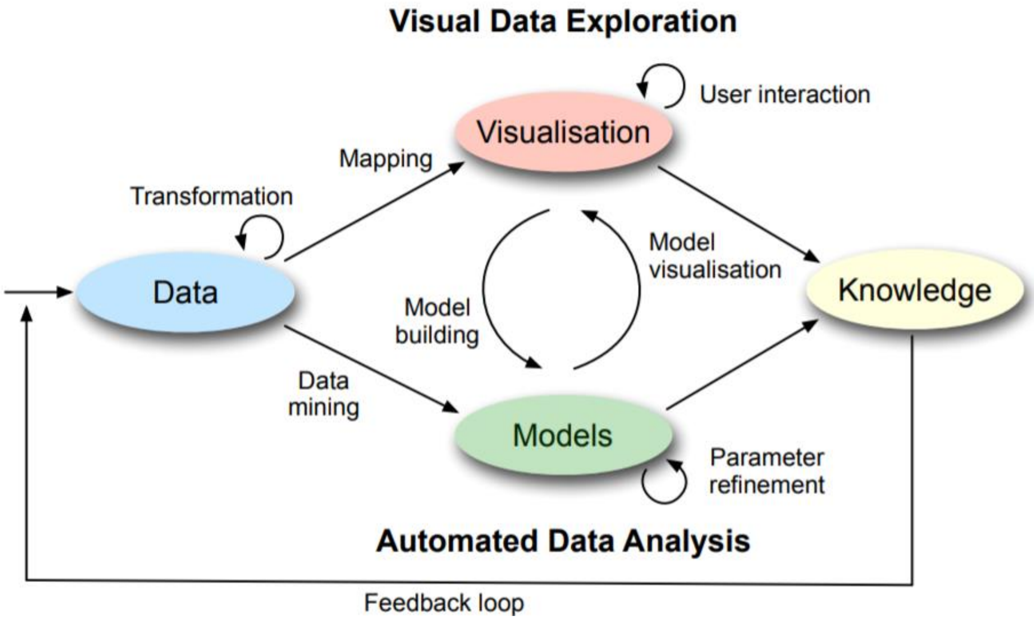
Visualisation can be subdivided into Scientific Visualisation (SV) and Information Visualisation (IV). Whilst IV is applied to more abstract, non-physical based data, SV is applied to physically based data and uses the location of a data point in combination with “a number of encoding techniques to form the representation” (PILGRIM, 2003).

IV is defined as ‘the use of computer supported interactive, visual representations of abstract data to amplify cognition’ (CARD; MACKINLAY; SHNEIDERMAN, 1999). As a computer science discipline, its solutions are therefore provided as software which address abstract visual data representations through visual artefacts. Its purpose is to accelerate rapid insight into the internal structure of data and causal relationships therein, through the use of visual representations and interactions, and to enable discoveries, explanations and facilitate decision making. It was originally meant as a ‘tool to permit handling large sets of scientific data and to enhance science’s ability to see phenomena in the data’ (CARD; MACKINLAY; SHNEIDERMAN, 1999).

However, SV is of particular interest for this research because of its relationship to 3D geometry and has many of the same attributes as Virtual Reality (VR). Both SV and VR attempt to facilitate interactive visual representation in order to amplify the cognition of data and spatial layout. Their primary requirement is to display data to the engineer in aid of their understanding of simulation results.

Visual representations ‘translate data into a visible form that highlight important features, including commonalities and anomalies’ (THOMAS; COOK, 2005 p.69). The fundamental idea is to create new ways of understanding information to enable the user to interact efficiently with large data collections and think deeply about complex problems and alternatives. As shown in Figure 22, knowledge is gained from data through the combination of automatic and visual analysis methods and human interaction. Often the first step is to process and transform data to derive different representations, followed by the application of visual or automatic analysis methods, alternatively, in such a way that one is always refining the other. (KEIM et al., 2010)

Figure 22: The visual analytics process (KEIM et al., 2010)



If the analyst chooses to begin with an automated method, he must then interact with the model by modifying parameters, selecting other analysis algorithms and evaluate findings. On the other hand, if he chooses to begin with visual data exploration, the generated hypothesis must be confirmed by an automated analysis.

3.2 VA in Building Construction

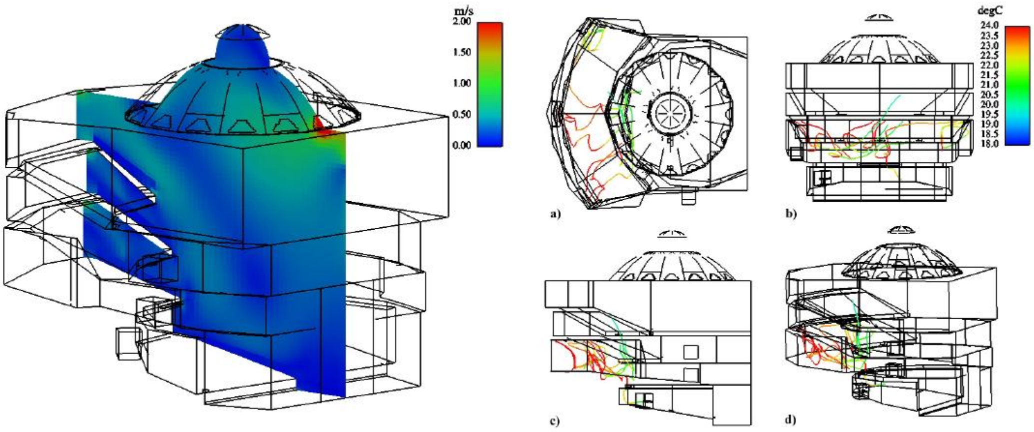
Visualisation holds strong potential for the field of construction engineering, as it ‘facilitates the communication of data which may have otherwise remained in an unintelligible form’ (PILGRIM, 2003). It will usually involve taking abstract information and rendering it in a form that can be seen to facilitate the analysis of structural behaviour, fluid dynamics, behaviour variation over time, and so forth.

> More recently, newer 3-D visualization techniques allowing the display of volumetric, multivariate and time-dependent behaviour have joined earlier display techniques in numerical analysis applications. In addition to the visualization algorithms themselves, this trend has been driven by increasing computing capabilities, which allow for more complex analyses. Today, the move towards further real-time 3-D graphics display capabilities is helping visualization become part of a more interactive approach to analysis. (GALLAGHER, 1994)

According to Gallagher (1994), visualization has irrevocably affected engineering practice in a myriad of ways. By allowing engineers to observe, through computer simulation, phenomena which may be difficult, expensive or dangerous to reproduce, it has produced a decrease in the costs of physical testing. Furthermore, it has produced greater integration of design analysis, facilitated the correction of design flaws, enabled the examination of complex phenomena not readily seen on an analysis model, allowed engineers to evaluate automated design changes and optimize the design itself and improved accuracy and productivity through a faster and more thorough design process.

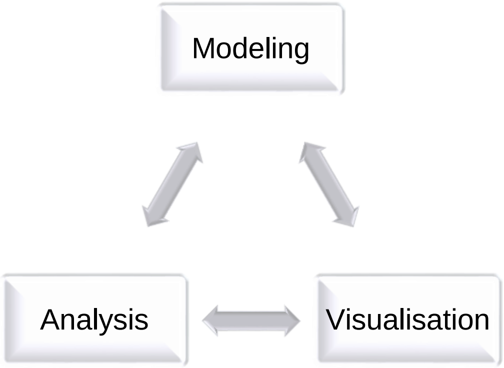
It is mainly divided into two main areas: Construction Information Communication and Construction Simulation, which includes the simulation of structure, fire performance, environmental impact, acoustics, maintenance, airflow, thermal analysis and automation systems. Considering that human perception is naturally geared towards the three dimensions of physical space, it is possible to comfortably adapt it to a fourth dimension such as colour variation. This technique is thus often used to help understand more complex phenomena, such as the temperature and flow of air through a room (Figure 23).

Figure 23: Air velocity distribution on a vertical section of an auditorium (left) and air movement with temperatures (right). (PILGRIM, 2003)



The traditional VA process comprehends the following cycle: modelling, or pre-processing, analysis, visualisation of results, or post-processing, and repeating the process until a satisfactory result is attained. Today, it is possible for the analysis itself to govern geometric change as well as visualize results as the analysis proceeds (Figure 24).

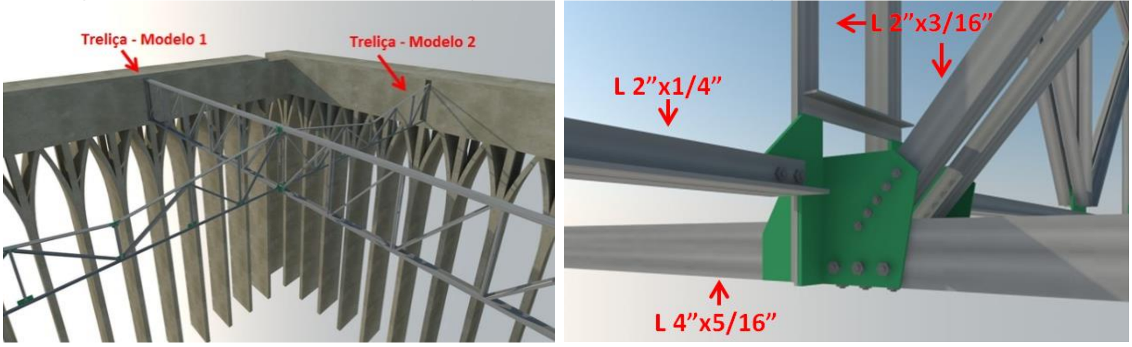
Figure 24: Integrated design, analysis and visualisation environment. (GALLAGHER, 1994)



The VA project frequently begins by constructing a geometric model (pre-processing), which describes the problem, such as a structural component, the idealization of an integrated circuit chip for heat transfer analysis or the air mass surrounding an aircraft wing for air flow analysis. The model is then used to create the data needed to perform an analysis. At this point, it is necessary to select the appropriate types of elements to represent the model's behaviour, create the mesh of these elements and define their material or physical properties. The same model may also be used for transient data analysis, such as changing boundary conditions or different loads.

After performing the analysis, it is necessary to determine the appropriate result visualisation technique. This post-processing phase can include operations of which the most common are result rendering, model transformation, animation and result field manipulation. Result rendering uses techniques such as tensor field streamlines, contour displays and isosurfaces to create images which represent the behaviour of a scale, a vector and so forth. A model transformation will permit the viewer to interactively modify the view, perspective, distance and position of the observer. An animation enables the display of behaviour over time and the navigation, or “walk-through” of a model in 3D space. Result field manipulations, on the other hand, make it possible to interact with the model by probing 3D locations within a model to display field data.

Figure 25: Dom Bosco Sanctuary 3D structural model. (OLIVEIRA et al., 2017a)



There are many examples of VA within Construction Information Communication. It can be used to facilitate the understanding of a structural system (OLIVEIRA et al., 2017a), exemplified by Figure 25; to better understand the distribution of loads (SÁNCHEZ-APARICIO et al., 2016) or even to interpret and visualize cloud-point data (CALAKLI; TAUBIN, 2012), as shown in Figure 26.

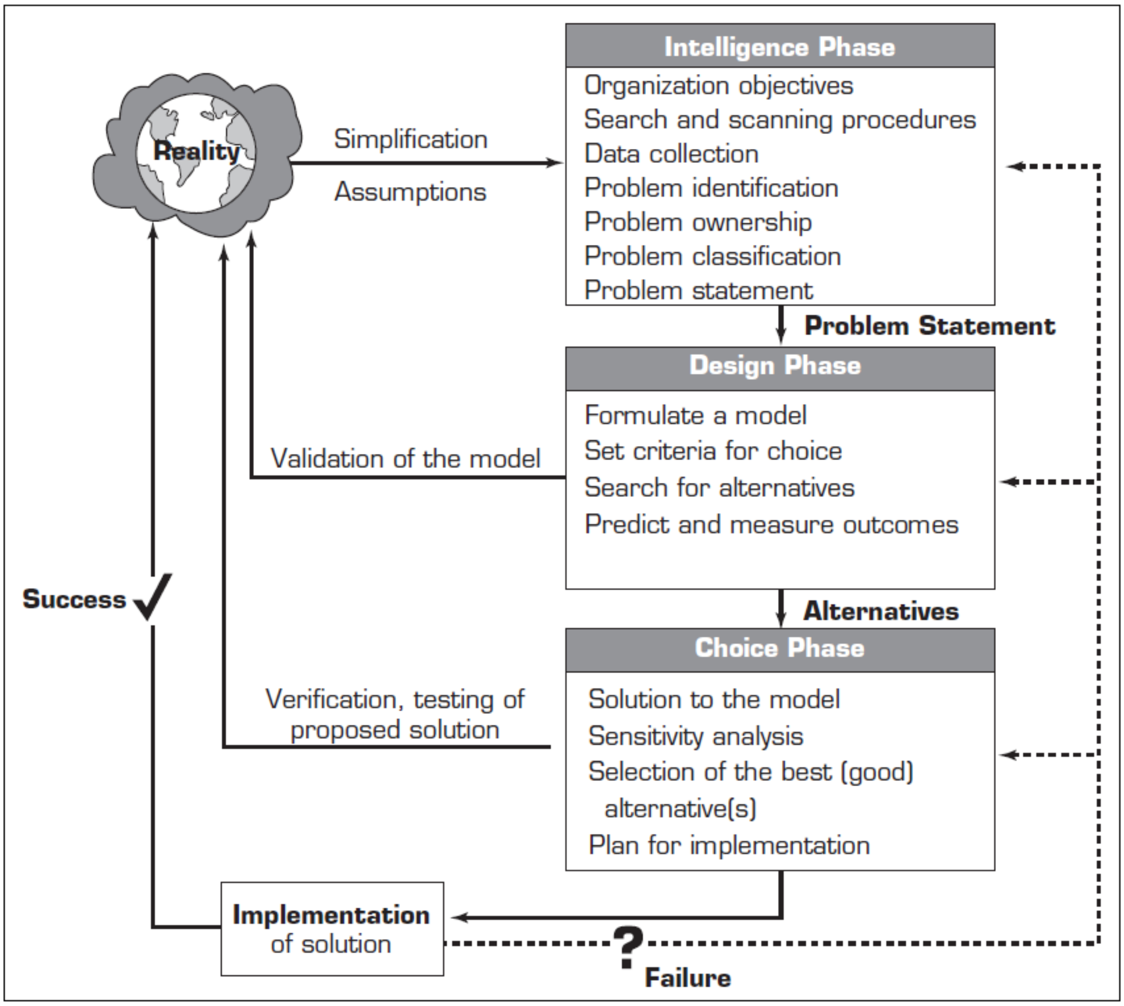
Figure 26: Cloud-point data visualization process. (CALAKLI; TAUBIN, 2012)

On the other hand, VA can also be used to simulate temperature and wind velocity (PILGRIM, 2003) or, in the case of this study, simulate degradation and maintenance decisions.

3.3 VA for Decision Making

According to Ruppert (2017), “decision making is defined as the process of selecting a course of action among a set of alternatives to address a given problem”. It is often considered as synonymous with “managing” and comprises three distinct, but interconnecting phases: intelligence, or finding occasions for making decisions; design, or finding possible courses of action; choice, which is considered the act of choosing among courses of action; and implementation (Figure 27).

Figure 27: The Decision-Making/Modelling Process (SHARDA; DELEN; TURBAN, 2014).



Although intelligence usually precedes design and design usually precedes choice, the cycle is often multidirectional, in such a way that the design phase may call for new intelligence activities or a choice may require a new design. (SIMON, 1960)

The process begins with the intelligence phase, in which the decision maker examines reality and identifies the problem. The phase includes the analysis of organization objectives, search and scanning procedures and data collection. During this phase, problem ownership, classification and statement are established. (SHARDA; DELEN; TURBAN, 2014)

During the design phase, it is necessary to construct a model that describes a real world problem, making assumptions that simplify reality and establishing the relationship between all variables. After model validation, it is necessary to determine the criteria that will be used to make a choice, identify and evaluate all alternative courses of action and predict possible outcomes. It is necessary to make sure that there are sufficient alternatives being taken into consideration, that their consequences can be reasonably predicted and that comparisons are properly done.

The choice phase comprehends the selection of the best course of action among those proposed by the design phase, which is then implemented to solve a real world problem.

Visualisation comes into play during the design phase to support analysis tasks – exploration and sense-making – and the knowledge transfer task – communication of data. While the former aims to extract knowledge from data, the latter addresses the transfer and presentation of the extracted knowledge. The ultimate goal is to support good decision making based on the understanding of information hidden in massive amounts of data

3.4 VA Software

The primary VA software used in this research was McNeel’s Rhinoceros 3D and its plug-in McNeel’s Grasshopper 3D. Rhinoceros 3D is a computer-aided design (CAD) software developed by Robert McNeel & Associates also known as “Rhino 3D” and is primarily used in industrial design, jewellery design and architectural trades. It uses the modelling by curves technique (NURBS) which allows the user to work with curves rather than polygons to create a three-dimensional surface. It focuses on mathematically producing precise representations of curves and freeform surfaces in computer graphics, thus enabling the optimization of the number of faces that form an object’s surface with the use of adaptive mesh.

Grasshopper 3D is a visual programming language and a parametric modelling tool also developed by Robert McNeel & Associates that runs within Rhino 3D. It uses algorithmic design to create 3D geometry can be used in parametric modelling for structural engineering, architecture and fabrication, building energy consumption and performance analysis for eco-friendly architecture. An associative or parametric 3D modelling approach means that a model can be changed according to different inputs or parameters, which create variations in the system without changing it. It can also be used, as is the case here, to associate numeric formulas and data to geometric information.

4 BIM

The visualisation capabilities of BIM and its ability to incorporate performance-over-time data make it the strongest tool for construction building analytics today.

The term BIM has progressed through many definitions. It has evolved from the three-dimensional visualisation aspect to workflow-specific tools used to capture, analyse and disseminate information in real time. It is no longer just a software, but a blend between processes, technologies and behaviours (HARDIN, 2015).

The term initially meant Building Information Modelling or Building Information Model, it has evolved over time to Building Information Management, due to the fact that BIM applications have progressed and BIM potential is now much wider than foreseen.

According to ADEB-VBA (2015), Building Information Management is a process in which different actors collaborate to develop more efficient buildings through effective construction processes, minimal waste production, minimal cost and proficient management. It is an information exchange platform where the key is not the model itself, but a system for collaborating, developing, managing and sharing information. It is similarly defined (AHMAD, 2013) as a system in which information is collected, stored, analysed, evaluated and exchanged.

A Building Information Model is a ‘three dimensional (3D) object-oriented model with embedded information’. It is a product comprising the connections of all the elements that compose a building, each with its own unique identifier which relates information about its properties and geometry, making up an information-rich database that links and controls model components. Its ‘value lies in the ability to aggregate, edit, sort and compile information to drive at better answers to design questions’ (HARDIN, 2015). This process is known as an object-based parametric modelling, where parameter rules define the context in which the object exists. The parametric BIM objects coexist to make up an intelligent building design within a virtual environment.

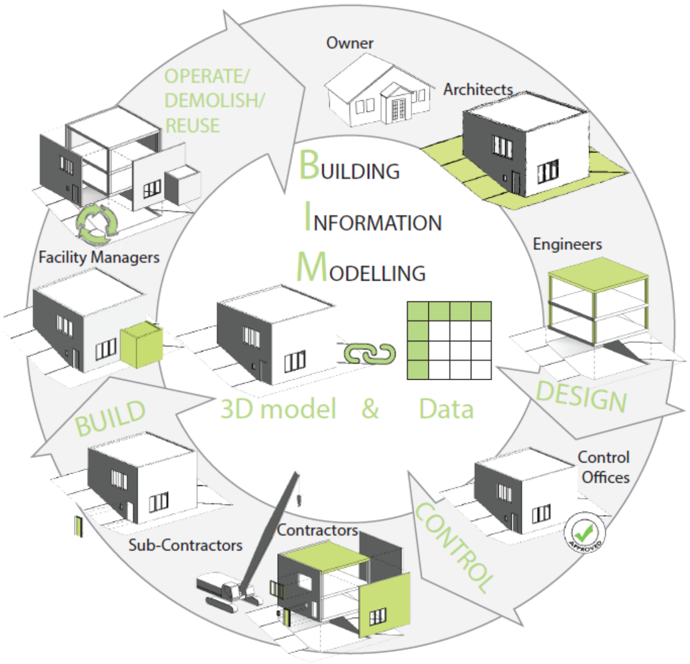
Building Information Modelling is defined as ‘the act of creating an electronic model of a facility for the purpose of visualization, engineering analysis, conflict analysis, code criteria checking, cost engineering, as-built product, budgeting and many other purposes’ (NIMBS COMMITTE, 2007). A BIM process can be applied any time during a facility’s lifecycle in order to achieve one or more purposes, such as: gather, generate, analyse, communicate and realise (KREIDER; MESSNER, 2013). The gathering process aims to collect and organise facility information by capturing its current status, quantifying or measuring the facility element, monitoring information regarding the performance of these elements and qualifying its status. During the generation process, it is necessary to create information about the facility, such as a three-dimensional model.

After generating all information necessary, analysis comes into play. It is essential to evaluate and coordinate facility elements, in order to ensure their harmony and efficiency, as well as forecast future performance and validate the accuracy of information. The final process is one of communication, or exchange of information. Information must be easily visualised, modified and documented. The information can then be used to make, fabricate or assemble a physical element or manipulate and inform element operation.

There are infinitive dimensions to a BIM process. What differentiates 3D BIM from 3D CAD is the data contained in the model, such as specifications and relations to other adjacent elements. The fourth dimension (4D) process links 3D objects to a time frame of scheduled works. 5D BIM is associated to cost management, recognising materials and assigning cost to components, whereas infinitive dimensions (nD) expand the application to other attributes, such as sustainability, acoustics, maintenance and lighting (KEHILY, 2016).

BIM is considered ‘one of the most promising developments in the architecture, engineering and construction industries’ (EASTMAN et al., 2012). Although heavily used during the building design phase to support, analyse and control construction and fabrication, it can also be used to model the entire lifecycle of a building (Figure 28) and ‘optimize facility management and maintenance by exporting relevant as-built building and equipment information’.

Figure 28: The building’s lifecycle and its stakeholders (ADEB-VBA, 2015)



In order to facilitate information exchange and interoperability, the building’s digital representation is essential. Such model information, along with technology and software improvement, have the potential to expand BIM use into other related workflows and processes, such as scheduling, logistics and estimation. Laser scanning technology has made data input more efficient, cloud-based information sharing has caused a big shift in collaboration methodologies and there is a constant push for data interconnectivity within industry, which impacts ‘the way construction is delivered and managed, from rigid and limited to flexible and scalable’ (HARDIN, 2015).

BIM information can be captured and used during the entire lifecycle of a facility and the data collected, graphical or not, can provide consistent, coordinated and computable information management not only during the design and construction stages, but for various FM activities, such as O&M. (YALCINKAYA et al., 2014)

FM is an ‘integrated approach to operating, maintaining, improving and adapting building and infrastructure assets in order to support the primary objectives of the occupants, owners and facility managers’ (PATACAS; DAWOOD; KASSEM, 2015). It comprises a variety of disciplines with an overall purpose to ensure occupants’ wellbeing by maximising building functions. However, existing FM systems, such as the electronic document management system (EDMS), the

CMMS, the energy maintenance system (EMS) or the building automation system (BAS), have no interoperability or compatibility with each other, resulting in error-prone processes. The benefits of the advanced visualisation and analysis capabilities of BIM can, therefore, support FM include quality control energy maintenance, space management, commissioning and closeout and maintenance and repair. (PÄRN; EDWARDS; SING, 2017)

BIM benefits for FM are highest with new construction projects and consist of design consistency and visualisation, clash detection, cost estimation, lean construction implementation and improved stakeholder collaboration. The Integrated Project Delivery (IPD) procurement method can promote collaboration and integration, facilitating BIM use through a contractual environment. However, IPD and most research involving BIM applications in FM is focused mainly in new buildings, where all design and execution was developed in a BIM model (KELLY et al., 2013).

There is a vast unexplored field involving BIM applications for FM of existing buildings with significant benefits, such as quality control, energy and space management, retrofit planning, emergency management, assessment and monitoring and valuable as-built heritage documentation. However, challenges are greater on account of incomplete, obsolete or fragmented building information. The inadequacy of as-built information can result in uncertain process results, ineffective project management and cost increases or time loss in remediation, retrofit and maintenance processes. (VOLK; STENGEL; SCHULTMANN, 2014)

BIM is not naturally considered for existing building interventions, yet studies show that this type of workflow can bring the same or more benefits to existing buildings as to new ones, considering that an existing building intervention often includes more information that needs to be consulted on-site as well as an equal number of project partners (architect, client, construction company, local authorities, subcontractors). BIM use can facilitate labour-intensive on-site surveys, manage collaborative intervention workflow and keep consistent records of results. (BARBOSA et al., 2016)

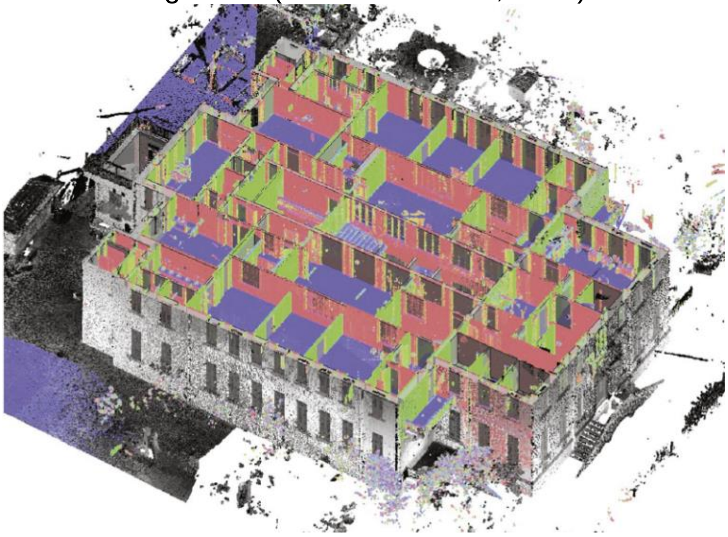
However, many challenges face BIM use in existing buildings. Manually modelling an existing building in a BIM environment is very time consuming as is the continuous updating of lifecycle information. Furthermore, integrating uncertain data, objects and relations concerning existing buildings requires specialized workers. Although benefitting from technological advances, this process still requires a lot of manual labour. (BARBOSA et al., 2016)

Two of the greatest technological advances involve data acquisition through laser scanning (TAPPONI et al., 2015) and (POCOBELLI et al., 2018), photogrammetry (MEZZINO et al., 2017), (ANGHELUȚĂ et al., 2017) and (POCOBELLI et al., 2018) and Geographical Information Systems (VACCA et al., 2018).

Photogrammetry is the estimation of the geometric and semantic properties of objects based on images or observations from similar sensors. In other words, it is a method which uses photography to measure distances. Usually executed with regular cameras, it is a process of collecting a series of images from slightly different viewpoints which is used to estimate 3D geometry or changes over time.

Laser scanning, although part of the photogrammetry universe, is a process through which a laser scanner distributes the laser beam both vertically and horizontally in an environment, systematically sweeping the surrounding area. Upon reaching an object, part of the energy reflects back to the scanner, which measures the distance between it and the object. Texture and colour are then incorporated using built-in or external cameras. When more than one scan is necessary, a collection of individual scans is linked to create a single representation called a Point Cloud. The Point Cloud is interpreted into a 3D object, as shown on Figure 29, so it can then be interpreted by the FM team (TAPPONI et al., 2015).

Figure 29 (BARBOSA et al., 2016)



The development of 3D GIS (Geographical Information Systems) have allowed not only better data management and more precise building information, but also a better understanding of the relative historical, urban and geographical contextualisation of heritage sites. 3D GIS is an evolution of a 2D territory management programme which ‘provides a robust data storage system, definition of topological and semantic relationships and spatial queries’ into a 3D visualisation platform (VACCA et al., 2018).

BIM usage has been suggested for existing building documentation in a cultural heritage context, in which buildings are modelled based on historical documents and on-site surveys as a way to study their historical value. We believe that BIM software should play a more important role in these buildings’ refurbishment and rehabilitation, bringing with it features such as digital cost estimation, data management, alternative calculations, quantity charts, quality assessment, deviation or deterioration analysis, vulnerability and collapse analysis, deconstruction planning, etc. (BARBOSA et al., 2016)

Heritage BIM is even more complex. The biggest challenge in the field is that heritage buildings tend to be ‘characterized by different historical layers, complex geometries and non-homogenous architectural elements’ (POCOBELLI et al., 2018). However, the necessity for cross-disciplinary knowledge in heritage building conservation processes calls for a model that allows both curators and stakeholders access to all related information and maintenance planning (WORRELL, 2015).

5 BUILDING DEPRECIATION AND DETERIORATION METHODS

Until the 70's, it was believed that no matter the environment and how reinforced concrete was shaped, its internal steel armour would be completely protected. Structure was designed to satisfy safety and stability requirements, however, because of the conviction that it would maintain its physical, mechanical and chemical properties, concepts such as service life and durability were irrelevant. Notwithstanding, the inevitable appearance of deterioration processes in reinforced structures became major issues and began to be researched across the world. (OLIVEIRA; PANTOJA; SANTORO, 2018)

Construction durability is directly influenced by factors such as construction, design and planning, correct execution, materials, environment and use. The Brazilian Concrete Standard, NBR 6118 (ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS, 2014), defines durability as the structure's ability to withstand predictable environmental influences. It gives us the definition of service life: the time period that the structure maintains its initial characteristics, as long as required maintenance and repairs are executed. Performance is additionally described as the structure's ability to preserve full use conditions, without damage which compromises partially or totally its designated use.

With age comes a decline in performance and service life, which may result in damages. Therefore, a key factor for durability is the execution of a series of activities designed to prevent performance loss caused by deterioration. These activities are called maintenance, which is executed to conserve or recuperate a construction and its parts' capacity to fulfil user needs and safety requirements. However, although buildings that were well built and received adequate preventive maintenance would manifest small damage over the years, the cost utilised to return the structure to its normal use conditions are estimated to be five times less than if there was no preventive maintenance. As a result, maintenance is considered fundamental for constructions to maintain their functions and is executed by performing regular inspections, assessing existing damage and determining the correct intervention. (FONSECA, 2007)

Nonetheless, the expense involved in maintenance is an important factor to take into consideration. Ultimately, however well planned and specified, if the budget is inadequate, there will be no maintenance and damage will eventually occur. Rising construction and maintenance costs, along with shrinking maintenance budgets, have accentuated the importance of minimising operation costs. Budget allocation can be optimised selecting the most cost-effective maintenance strategies. (FLORES-COLEN; DE BRITO, 2010)

There are three types of maintenance, two proactive and one reactive. Preventive maintenance is predefined, scheduled maintenance performed at regular intervals, which reduces the need for non-planned works. Predictive maintenance, on the other hand, is performed according to planned inspections and has been useful for efficient maintenance budget use and reducing lifecycle costs. Reactive maintenance is associated with unexpected anomaly corrections and is almost always an emergency procedure which can lead to extra cost and must be avoided. The first two preventive maintenance strategies prevent problems before they occur and effectively reduce service life cost. (FLORES-COLEN; DE BRITO, 2010)

There is a large proportion of modernist structures in a state of physical depreciation and threatened structural performance. For this reason, scenario simulation has become essential, through the precise record of the construction's current status, the qualitative and quantitative physical depreciation evaluation, and the pathological progression prediction. (SANTORO; PANTOJA, 2018)

Depreciation is defined as the loss of value due to building element reproduction or substitution costs resulting from physical deterioration, functional or external obsolescence or a combination of the three.

Physical depreciation is related to age deterioration due to subjected use and lack of conservation execution or the occurrence of accidents or disasters. Amongst physical depreciation causes are: ageing, wear, obsolescence, function alteration, interaction between different materials, and even natural disaster. This type of depreciation can be divided into curable and non-curable. A depreciation is considered curable if the cost of substituting a deteriorated element is equal to or smaller than the increase in building value when doing so, and non-curable if substitution is not economically or technically viable, such as building structure. The building’s financial value is, therefore, intrinsically linked to the study of its physical depreciation factor. (BRAGA, 2015)

The methods, or criteria, used to calculate physical financial depreciation abound, however, the chosen method for this research demands another analysis, the CS (Conservation Status), which, for the current research, will be obtained through the Deterioration Degree (Parametric GDE-UnB) or the Condition Rating (Dutch Standard).

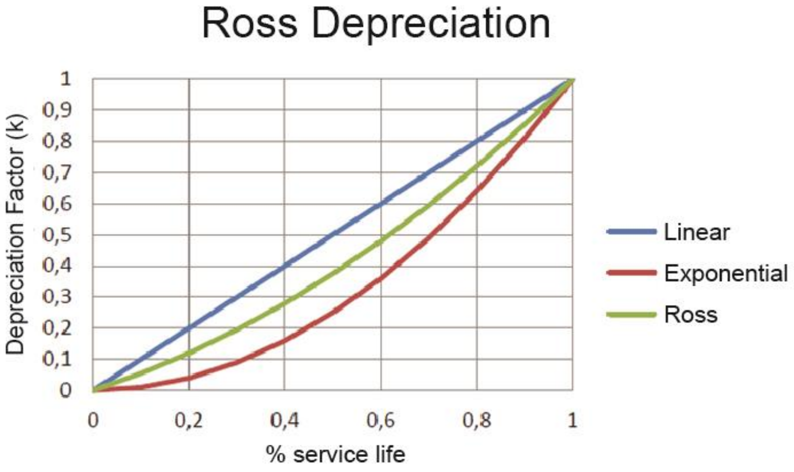
5.1 Financial Depreciation Methods

5.1.1 Linear, Exponential and Ross Depreciation Methods

Most likely the simplest and most-used depreciation method in finance, the linear depreciation method takes into account only two variables, age and projected service life. The depreciation factor (k) is obtained by dividing the age by the service life resulting in a linear diagram. This method is valid for some cases, however it is not considered very efficient when dealing with real-estate, as it can provide very inaccurate results. According to this method, facilities at 20% of projected service life would be 20% depreciated and at 40% of service life would be 40% depreciated. However, degradation is not constant. Building elements take a long time to begin deteriorating and accelerate with time, especially with no maintenance. (PIMENTA, 2011)

The exponential depreciation method uses the same philosophy as the linear model, while attempting to obtain results closer to the actual real-estate market, and consists of the squaring function of age over projected service life. The Ross model associated the previous two methods and generated depreciation through their arithmetic average (Figure 30).

Figure 30: Translation of the Linear, Exponential and Ross method comparison (PIMENTA, 2011)



Notwithstanding, evidence suggests that identical constructions may not decay in similar manner, making it necessary to develop different methods which take into account additional variables, such as conservation status, projected lifespan, service life, construction quality and maintenance regularity.

5.1.2 Ross-Heidecke Method

Instead of refining the Ross method even more, Heidecke introduced a new variable, Conservation Status, in order to better define physical degradation behaviour. To this end, he introduced a conservation status scale, where 0.00% corresponded to new and 100,00% to worthless, as seen in Table 1.

Table 1: Translation of the Conservation Status Scale. Source: Pimenta (2011).

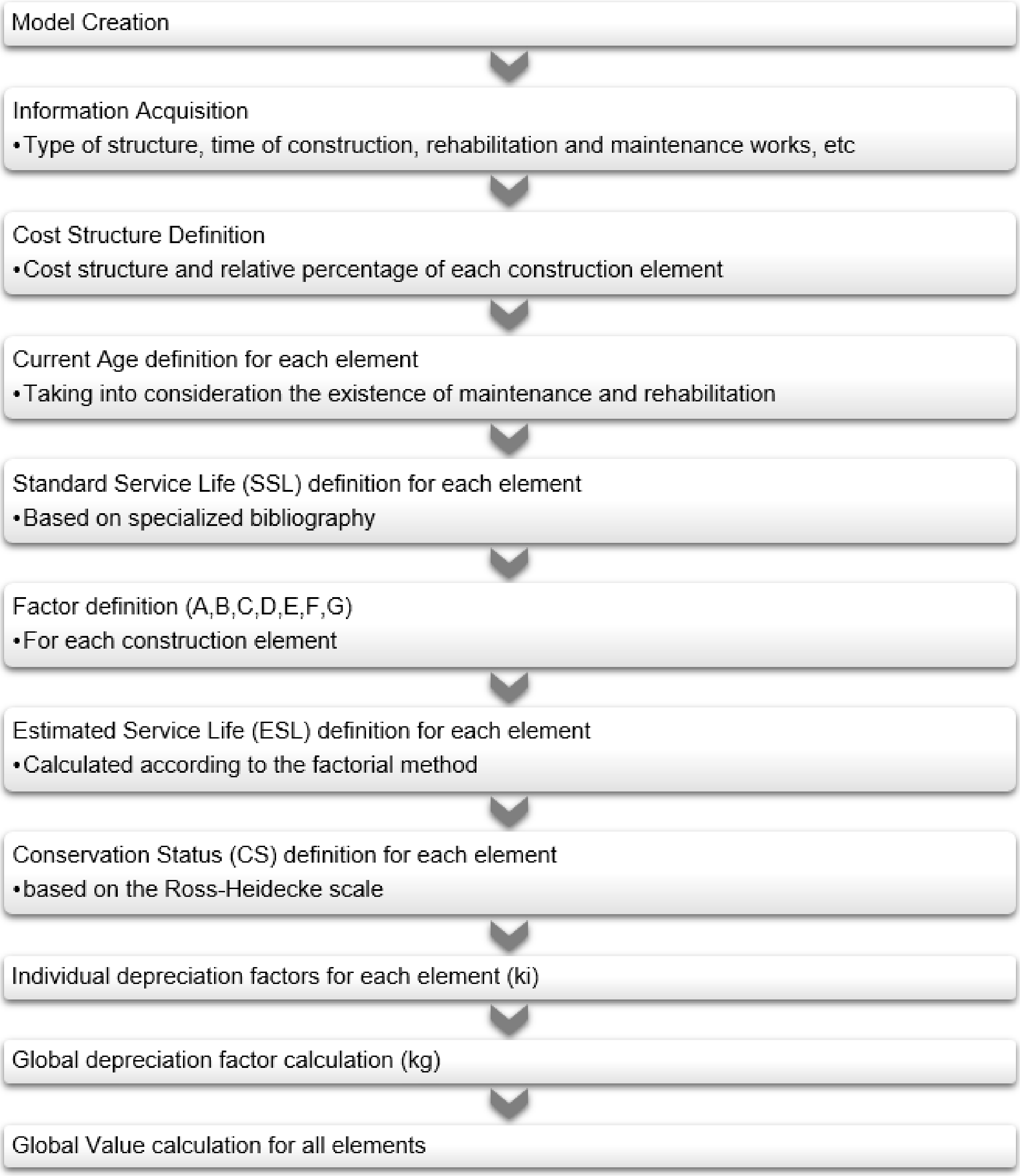
C	Conservation Status
0.00%	New
0.32%	Between new and regular
2.52%	Regular
8.09%	Between regular and simple repairs
18.10%	Simple repairs
33.20%	Between simple and important repairs
52.60%	Important repairs
75.20%	Between important repairs and worthless
100.00%	Worthless

The Ross-Heidecke Model is based on the relation between age and conservation status. According to this method, maintenance and restoration are not fully capable of completely recuperating construction value as it only prolongs service life, thus well-maintained properties depreciate more slowly than poorly-maintained ones. (PEREIRA, 2013)

5.1.3 Ross-Heidecke Expansions

Pimenta (2011) expanded the Ross-Heidecke Model by calculating physical depreciation for each construction element and then using the weighted average to determine total depreciation and is calculated according to the flow-chart presented in Figure 31.

Figure 31: Translation of the Ross-Heidecke flow-chart as adapted by Pereira (2013)



Each element, or parameter, is weighted according to its cost percentage during initial construction, and then multiplied by the depreciation factor attributed by a specialist. The number of parameters analysed does not have to encompass the entire construction, as long as it is possible to determine the cost percentage of each individual parameter in relation to the sum.

Initially, information was gathered about the building: the type of building; the history of the construction and whether there had been maintenance or repairs. Subsequently, the cost structure was defined, in order to attribute a weight to each parameter and the percentage they represented within the total structure (Ei) according to an estimation of initial costs. The current age was then established of the different parameter (AGE) by taking into consideration if it had received maintenance or repairs, and defined their ESL. The following step was the definition of each parameter's conservation status (CSi). In this case, the evaluator's experience is of the uttermost importance, so as to adequately quantify the property's physical depreciation. In the Ross-Heidecke model, the conservation status is defined for the entire property, wherein with Pimenta's model, we define the status for each parameter separately.

$$k_i = \frac{1}{2}\left[\frac{AGE}{ELS} + \left(\frac{AGE}{ESL}\right)^2\right] + \left[1 - \frac{1}{2}\left[\frac{AGE}{ESL} + \left(\frac{AGE}{ESL}\right)^2\right]\right] \times CS_i$$

Once the value for each parameter has been defined, it was possible to calculate the physical depreciation factor of each element (ki) with the previous formula.

From the cost structure, the individual depreciation factors (ki) were established and their percentage of relative cost to the global property (Ei). With these integers, it is then possible to calculate the global depreciation factor, kg, according to the subsequent formula, where i represents the parameter and j the number of parameters analysed.

$$k_g = \sum_{i=1}^{j} [k_i \times E_i]$$

Further expansion by Pereira (2013), suggests manipulating the variable with the greatest degree of influence on the final result, the service life, to which he applies a deterministic method known as the factor method. It was regulated by ISO 15.686-2 (ISO, 2011), and is probably the most used service life estimation method today. Even with some criticism as to the over simplification of reality, the method is quite straightforward and flexible and represents the only standardised method to obtain the estimated service life from experimental data. Consider the following expression, where SSL stands for Standard Service Life, which is multiplied by performance altering factors to achieve the ESL:

$$\mathrm{ESL} = \mathrm{SSL} \times \mathrm{A} \times \mathrm{B} \times \mathrm{C} \times \mathrm{D} \times \mathrm{E} \times \mathrm{F} \times \mathrm{G}$$

The seven factors which can affect service life are: material quality, project quality, execution quality, internal environment quality, external environment quality, operation quality and maintenance quality. ISO 15.686-1 recommends using manufacturer provided SSL values, however, in the absence of this information, it is necessary to review values applied in National and International Standards or specified literature. The weights assigned to each factor are also recommended by ISO 15.686-1: 0.8 for unfavourable conditions, 1.0 for normal conditions and 1.2 for favourable conditions.

It is possible to establish a behavioural history of depreciation systems and predict consequences according to status changes (such as maintenance, reinforcement, restoration, and even natural disasters) by manipulating models attributes (such as service life, conservation status and age), and formulating predictive simulations for decision making and conservation programs.

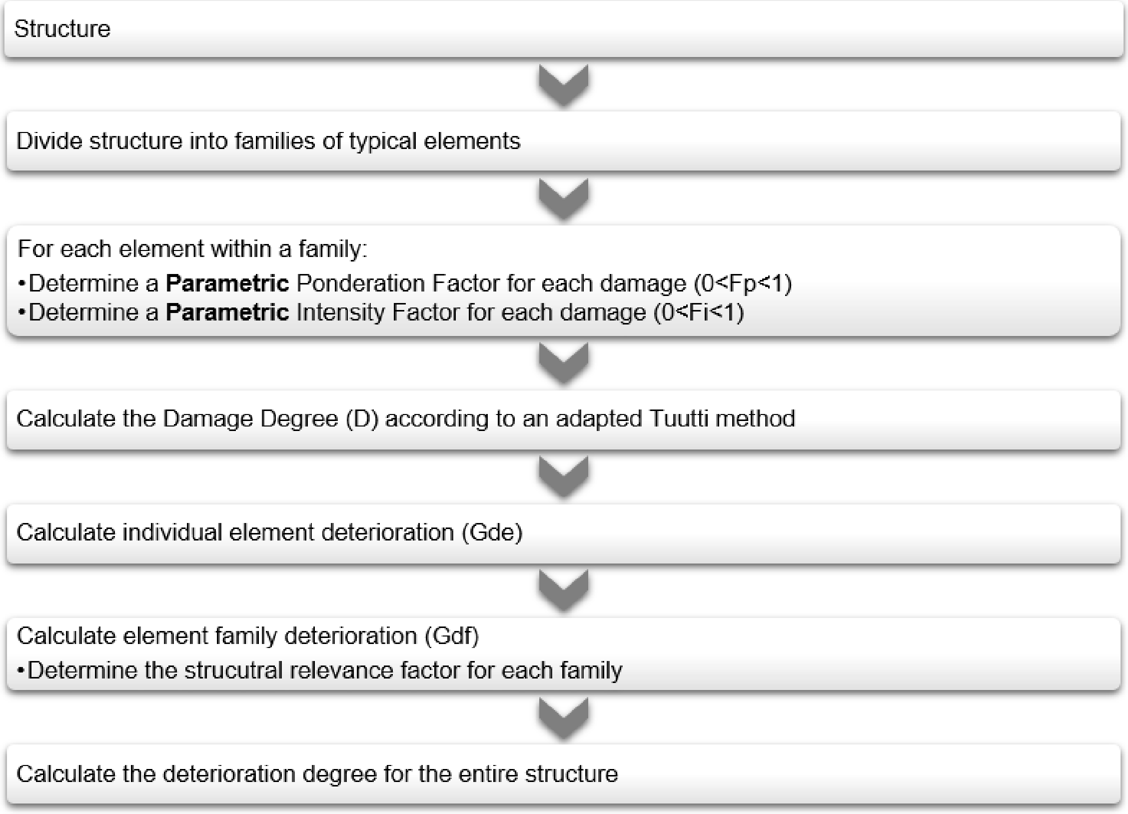
5.2 Deterioration Methods

Two deterioration methods were considered and analysed for this study, the Parametric GDE-UnB (PANTOJA et al., 2018) and the Parametric Dutch Standard (STRAUB, 2009). The former, a method based on the quantification of physical damage evolution throughout a structure’s service life; the latter, a condition assessment method based on the importance or urgency of said damage.

5.2.1 Parametric Brazilian GDE-UnB Method for Physical Deterioration

Created by Castro (1994) and modified by Pantoja et al. (2018) the parametric GDE-UnB method aims to quantitatively evaluate conventional reinforced concrete structures, by quantifying the deterioration degree of a structure's components, component families as well as the structure as a whole, as shown in Figure 32.

Figure 32: Translation and parameterization of the GDE-UnB Flow Chart (CASTRO, 1994)



The structure must be subdivided into component families (pillars, beams, foundations, etc.) and each family further subdivided into individual elements. Each element must then be inspected and each type of damage recorded according to extent and intensity. Subsequently, for each type of damage or pathology found, it is necessary to attribute a ponderation factor (Fp) according to TABLE 1 and an importance factor (Fi) according to TABLE 2.

Table 2: Translation and parameterization of the Fp for each Damage Type (PANTOJA et al., 2018)

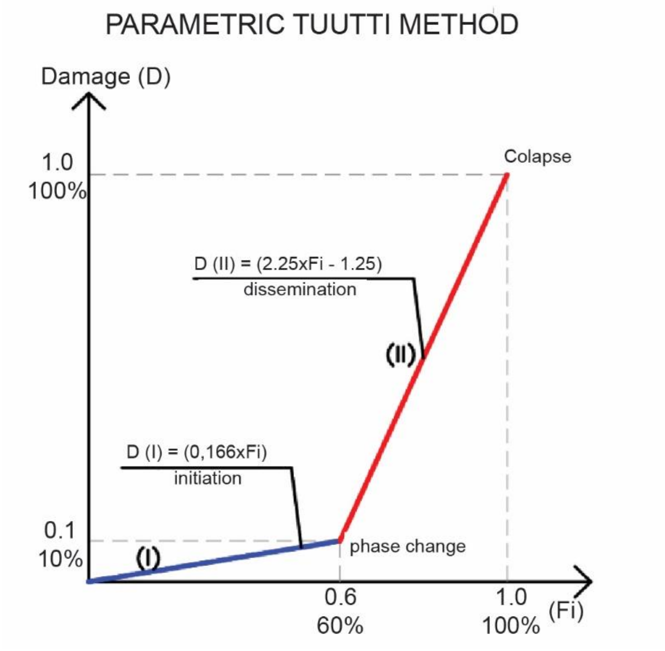
Structural Family Damage	Pillars	Beams	Slabs	Stairs and Ramps	Retaining Wall	Superior and Inferior Reservoirs	Foundation	Expansion Joint	Architectural Elements
Carbonation	0,6	0,6	0,6	0,6	0,6	0,6	0,6		0,6
Deficient coverage	0,6	0,6	0,6	0,6	0,6	0,6	0,6		0,6
Chloride contamination	0,8	0,8	0,6	0,8	0,8	0,8	0,8		0,8
Reinforcement corrosion	1	1	1	1	1	1	1		1
Disaggregation	0,6	0,6	0,6	0,6	0,6	0,6	0,6		0,6
Peeling; shedding	0,6	0,6	0,6	0,6	0,6	1	0,6		0,6
Geometry deviation	0,8				0,6				
Efflorescence	0,4	0,4	0,4	0,4	0,4	0,4	0,4		0,4
Manufacture defect	0,6	0,4	0,4	0,4	0,4	0,6	0,6		0,4
Cracks	0,2 a 1	0,2 a 1	0,2 a 1	0,2 a 1	0,2 a 1	0,2 a 1	0,2 a 1		0,2 a 1
Stains	0,6	0,6	0,6	0,6	0,6				0,6
Differential settlement	1						1		
Evidence of crushing	1	0,8		0,8	1		1		1
Humidity at base	0,6						0,6		
Displacement		1	1	1					
Humidity		0,6	0,6	0,6	0,6			1	0,6
Thrust displacement					1				
Deficient waterproofing						0,8			
Leakage						1			
Joint obstruction								1	

Table 3: Translation and parameterization of the Fi for each Damage Type (PANTOJA et al., 2018)

Element Damage Classification	Fi
No damages	0
Slight damages	0,25
Tolerable damages	0,5
Grave damages	0,75
Critical	1

In order to calculate physical deterioration, the method takes into account a model proposed by Tuutti (1982), based on the evolution of the reinforcement corrosion process, which was later expanded to include, generically, the entire structure`s deterioration process. According to this method, a structure`s deterioration evolved in two distinct stages: damage initiation and dissemination, exemplified by Figure 33, where Fp = 1. During the initiation phase, environmental agents slowly penetrate the concrete’s microstructure until damage occurs. The damage in this phase is very subtle and the degradation speed, gradual, without significant threats to the structure. The dissemination phase evolves much faster due to the deterioration process' acceleration factor and may cause significant damage and even loss of structural resistance. (PANTOJA et al., 2018)

Figure 33: Parametric Tuutti Line Chart (PANTOJA et al., 2018)



The Damage Distribution (D) was thus calculated for each type of damage a parameterized Tuutti (1982) Method, where:

- For Fi ≤ 0,6, D = 0,166 · Fi · Fp
- For Fi > 0,6, D = | (2,25 − Fi) – Fp |

Lopes (1998) further developed the method in order to include deterioration degree for an isolated element (G_{de}), calculated according to the following formula:

$$G_{de} = D_{max} \times \left(1 + \frac{\sum_{i=1}^{m} D_{(i)} - D_{max}}{\sum_{i=1}^{m} D_{(i)}}\right)$$

Where:

- D_{max} = Highest damage
- m = number of types of damage detected
- $D_{(i)}$ = damage for each element

Boldo (2002) similarly developed the method in order to calculate the deterioration degree for each structural family (G_{df}) as follows:

$$G_{df} = G_{de\,max} \times \left(1 + \frac{\sum_{i=1}^{m} G_{de\,(i)} - G_{de\,max}}{\sum_{i=1}^{m} G_{de\,(i)}}\right)$$

Where:

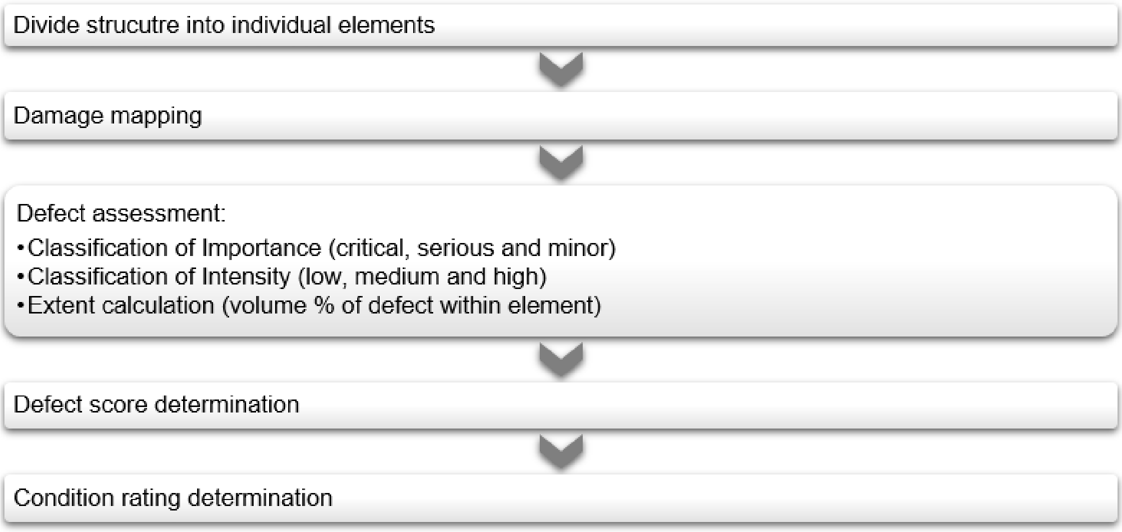
- G_{de} max = Highest element deterioration degree
- m = number of elements
- $G_{de(i)}$ = deterioration degree for each element

In order to calculate the deterioration degree for the entire structure (G_d), it is necessary to determine structural relevance factors (Fr) according to the importance of each family of elements. However, since the use case for this paper takes into account only pillars and beams, both with the same relevance factor, the G_d will be the average of all considered G_{df}s.

5.2.2 Parametric Dutch Standard for Deterioration Urgency

The Dutch Standard was initiated in 2002 by the Dutch Government Buildings Agency with the objective to standardise the condition assessment of building components and facilitate the transfer of knowledge between property managers within and between organisations. Its aim was to ‘provide property managers with unambiguous, reliable information about the technical status of buildings based on assessed defects’ (STRAUB, 2009). It is intended for assessing all components of large-scale buildings, however for this paper, it will be used to analyse only structural components.

Figure 34: Adapted Dutch Standard flow chart (STRAUB, 2009)



Condition assessments need to be performed visually by trained inspectors, who must first assess defects in order to attribute condition parameters, such as importance, intensity and extent of defects, which will in turn provide the respective Condition Rating (CR). The importance of a defect is divided into minor (TABLE 3), serious (TABLE 4) and critical (TABLE 5) and it indicates to what extent it influences the functioning of a building. Defects to finishes are considered minor defects, and while serious defects mean the degradation of a building's component without directly harming its function, critical defects do significantly threaten its function. The intensity of defects deals with the degradation process and can be considered low if the defect is hardly visible, medium if it is progressing and high if it cannot progress any further.

Table 4: Parameterization of the condition ratings for minor defects (STRAUB, 2009)

Intensity	**< 2%**	**2%-10%**	**10%-30%**	**30%-70%**	**≥ 70%**
Low	0.17	0.17	0.17	0.17	0.33
Middle	0.17	0.17	0.17	0.33	0.50
High	0.17	0.17	0.33	0.50	0.67

Table 5: Parameterization of the condition ratings for serious defects (STRAUB, 2009)

Intensity	**< 2%**	**2%-10%**	**10%-30%**	**30%-70%**	**≥ 70%**
Low	0.17	017	0.17	033	0.5
Middle	0.17	0.17	0.33	0.50	0.67
High	0.17	0.33	0.50	0.67	0.83

Table 6: Parameterization of the condition ratings for critical defects (STRAUB, 2009)

Intensity	**< 2%**	**2%-10%**	**10%-30%**	**30%-70%**	**≥ 70%**
Low	0.17	0.17	0.33	0.50	0.67
Middle	0.17	0.33	0.50	0.67	0.83
High	0.33	0.50	0.67	0.83	1

The greatest contribution to this study however, is the extent consideration. By taking into account extent, or in this case the volume, of defects, it is possible to aggravate or alleviate the CR of defects according to the damaged percentage of each element.

5.3 Proposed Expansion – Hybrid Method

The Ross-Heidecke method still requires refinement and one of its bigger issues is its subjectivity, as its CS (Conservation Status) is still highly dependent on an expert's opinion. Therefore, in order to accredit the method with greater objectivity, the CS was substituted by a combination of the two previous deterioration methods.

Initially, the expanded Ross-Heidecke method was followed according to both Pimenta (2011) and Pereira (2013). Ass necessary structural and environmental information was acquired. Since all analysed elements are pre-fabricated reinforced or pre-stressed concrete, they were estimated to have the same cost per volume and as such the volume of each element also represents its cost with regards to the entire structure. The current age, the SSL and the ESL were then determined as usual. The deterioration methods came into play when assigning a CS. Each element was subdivided into a mesh of voxels (10x10x10cm cubes) and each damage was mapped.

The parametric Dutch Standard and GDE-UnB methods were then used separately and together in order to determine the deterioration degree for each element and then compared. The GDE-UnB was calculated according to the intensity and ponderation factors of each defect, while the Dutch Standard was used to determine a CR for each voxel according to its volume in relation to the entire element, its importance and intensity. Both were then inputted into the Tuutti chart to calculate a D, which in turn was inputted into the GDE-UnB formula to calculate a G_{de} for each element. The results were then compared to determine the most accurate method, as explained in Section 6.3.

The G_{de} based on a hybrid approach between the parametric GDE-UnB and the Dutch Standard was chosen due to the fact that it takes into account defect volume. It was thus inputted into the Ross-Heidecke formula in place of the CS to calculate kie, whose average and weighted mean in turn provided the kif and the kg respectively.

Figure 35: Proposed hybrid method for depreciation analysis (private collection)

Model Creation

Information Acquisition
- Type of structure, time of construction, rehabilitation and maintenance works, among others

Cost Structure Definition
- Cost structure and relative percentage of each construction element

Current Age definition for each element
- Taking into consideration the existence of maintenance and rehabilitation

Standard Service Life (SSL) definition for each element
- Based on specialized bibliography

Factor Definition (A,B,C,D,E,F,G)
- For each construction element

Estimated Service Life (ESL) definition for each element
- Calculated according to the factorial method

Substitute the Conservation Status (CS) for each element by the GDE
- Condition rating (CR) determination according to the parametric Dutch Standard
  - Damage mapping and assessment according to importance, intensity and extent classifications
- Calculate Gde of each element from an addapted D:
  - Calculate the Damage Degree (D) by inserting the CR into the Tuutti chart

Individual depreciation factors calculation for each element (kie)

Individual depreciation factors calculation for each element (kif)

Global depreciation factor calculation (kg)

Global value calculation for all elements

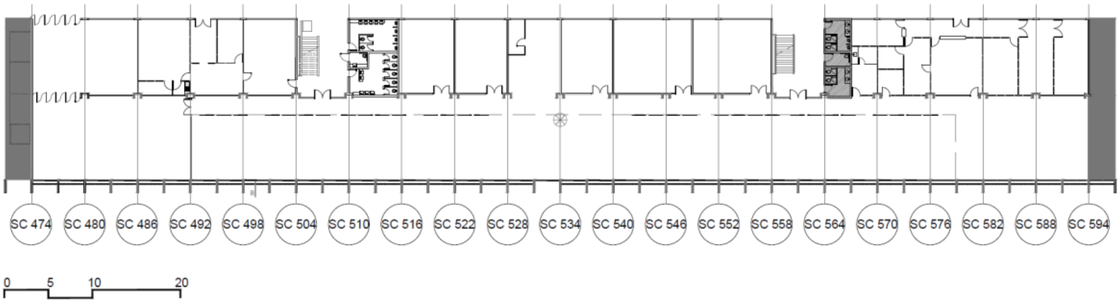
6 USE CASE

The chosen use case is the Architecture College within the University of Brasilia's ICC (Figure 36). The ICC is composed of two symmetric and homogeneous buildings whose floorplan shape represents an arch in the middle with rectangular extremities in the exact opposite manner of the Brasília's Pilot Plan. The two constructions are parallel and separated by a 16-meter strip of gardens and circulation. The main entrances are located at the both ends of the arch, whose interior is marked with empty spaces, mezzanines and large cantilevered ramps. There are two secondary entrances ate both extremities. The building's architecture is derived from its structure, where beams, slabs and pillars define architectural composition and form, composed of a prestressed frame system, repeated every three meters through the entire building span. (BORGES, 2015)

Figure 36: Architecture College – Sections 474 to 594

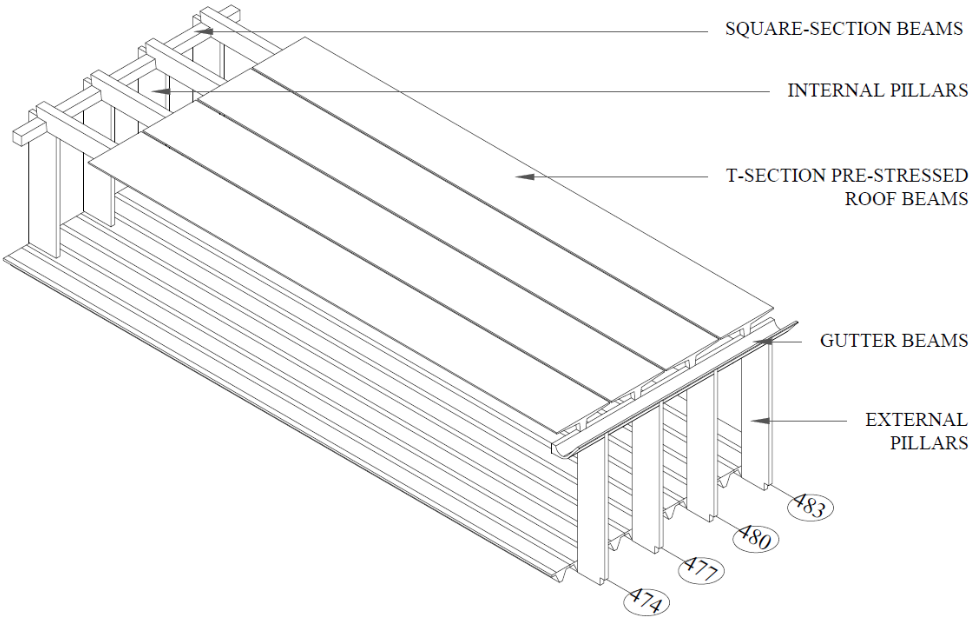
The ICC is subdivided into seven colleges and we chose the Architecture College as our test subject. It is comprised of a 120-meter section of the eastern bloc, starting at meter 474 and ending at 594 (Figure 37).

Figure 37: Architecture College Floor Plan (private collection)



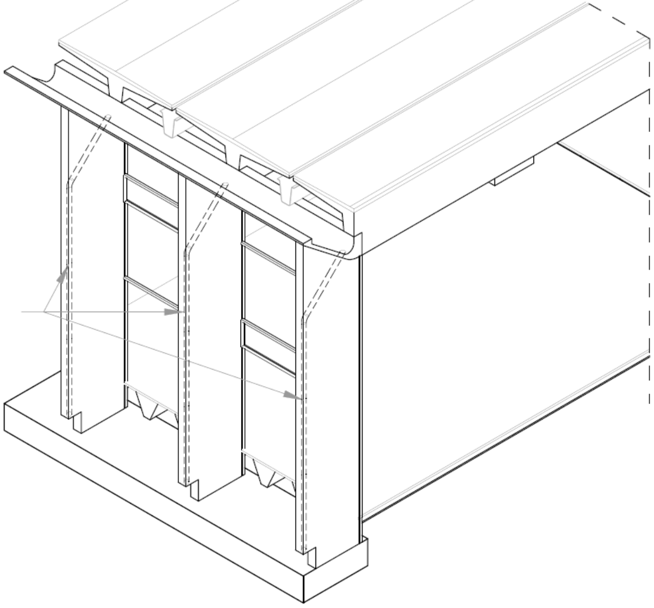
The ICC’s structure is comprised of 4 lines of pre-fabricated rectangular pillars, spaced 3 meters apart, measuring 0,20x1,50 meters in floorplan and with a 10-meter height. Five structural elements were chosen as seen in Figure 38 – external and internal pillars, square-section beams, gutter beams and t-section beams.

Figure 38: Structural isometric (private collection)



Their production already included fittings for all beams and slabs. Rainwater drainage pipes were incorporated into the external pillars at a 45º angle, as shown in Figure 39.

Figure 39: Rainwater drainage pipes (private collection)

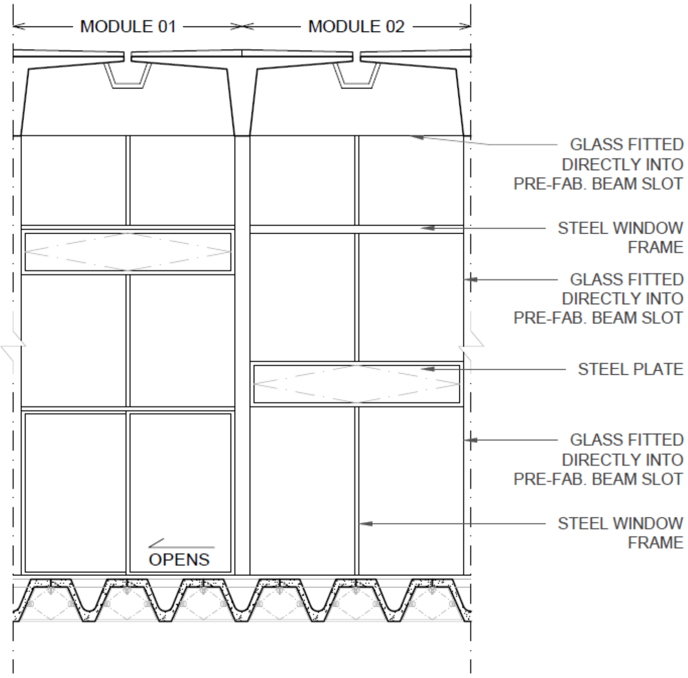


The pillars support the t-section pre-stressed roof beams. These beams span 29,5 meters and are isostatic, with three strengthening girders along their span (Figure 40). Between the pillar and the roof beams are curved beams, which work both structurally as well as rain gutters, which we shall call gutter-beams.

Figure 40: strengthening girders (private collection)

The atrium at the centre of the Architecture College has two window configurations between pillars, which we shall call Module 01 and Module 02 (Figure 41). Although some glass panels are protected by frames, many are slotted directly into pillars and beams and thus are directly affected by structural movement.

Figure 41: Window configurations (private collection)



7 RESULTS

The results were subdivided into four main stages: the inspection and mapping of element pathologies through physical inspection and photographic evidence; the scripting, comparison and analysis of different degradation and depreciation methods, from which originated a hybrid methodology; the graphic mapping and representation and visual analytics of the original methodology on the use case model and the scenario simulations for decision making.

7.1 Inspections and mapping

Visual inspections were made from the roof, where the damage to the t-section beams and the gutter beams were mapped. The remaining structure was then photographed from ground level and manually mapped into Grasshopper.

7.1.1 External Pillars

Almost all external pillars analysed showed signs of segregation due to manufacture flaws (Figure 42 to Figure 44), whether due to an error in component dosage, to inadequate concrete pumping, which leads to gravel clumping, or to faulty use of concrete vibrators, which can result in a heterogeneous mixture.

Figure 42: segregation due to manufacture flaws on Pillar 474 (private collection)

Figure 43: segregation due to manufacture flaws on Pillar 539 (private collection)

Figure 44: segregation due to manufacture flaws on Pillar 561 (private collection)

Because of the experimental characteristic of the building’s pre-fabrication, all similar elements present analogous defects. In all pillars, the defect is at its gravest where the rainwater pipes are embedded, due to probable vibration defects. According to the parameterized GDE-UnB Method, the respective Fp for pillars is 0.60 and the perceived Fi was 0.75, or grave damages. For the Dutch Standard, the same manufacture defect was considered a serious defect with a high intensity, however, the CR was determined by the affected volume of each pillar.

Deficient coverage, along with concrete segregation, can also cause reinforcement corrosion (Figure 45 to Figure 47) due to its consequential exposure to humidity or harmful gases. The process is of an electrochemical nature which modifies the steel’s properties and causes it to lose resilience. According to the GDE-UnB, the recommended Fp for pathologies of this nature is 1.00 and the chosen Fi is 0.75. With regards to the Dutch Standard, the corresponding defect was considered critical with high intensity and thus calculated according to the affected volume.

Figure 45: reinforcement corrosion on Pillar 483 (private collection)

Figure 46: reinforcement corrosion on Pillar 552 (private collection)

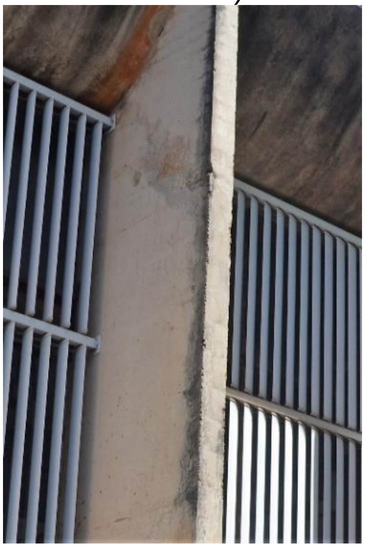
Figure 47: reinforcement corrosion on Pillar 570 (private collection)

Efflorescence (Figure 48 to Figure 50) is also caused mainly by humidity infiltration, which causes a concentration on the concrete’s surface of salts and white chalk, present in most cements. The humidity dissolves the calcium salts within the concrete which migrate to the surface through a capillary action. The salts, after reaching the surface, react with carbon gas and evaporate, leaving a deposit of hardened minerals. The defects do not harm the structure, but can be aesthetically displeasing. Therefore, the recommended Fp is 0.40 and the chosen intensity 0.75. Alternately, for the Dutch Standard, the defect was considered minor, but with high intensity.

Figure 48: Efflorescence on Pillar 480 (Private collection)

Figure 49: Efflorescence on Pillar 501 (Private collection)

Figure 50: Efflorescence on Pillar 576 (Private collection)



According to photographic evidence, each defect was roughly mapped and its volume calculated, as shown in Table 7.

Table 7: Defect volume percentage within each external pillar

	Pathology %			
Section	Manufacture Flaw	Efflorescence	Reinforcement Corrosion	Remaining
474	6.0	3.7	0.0	90.3
477	6.9	12.8	0.0	80.3
480	3.7	12.8	0.2	83.3
483	3.7	12.8	0.2	83.3
486	5.7	4.5	0.0	89.8
489	3.5	13.8	0.0	82.7
492	5.7	4.5	0.0	89.8
495	3.0	13.8	0.0	83.2
498	5.4	0.6	0.0	94.0
501	6.8	6.8	0.0	86.4
504	9.6	3.5	0.0	86.9
507	5.5	4.3	0.0	90.2
510	5.5	0.0	0.0	94.5
513	5.5	6.9	0.0	87.6
516	5.5	0.0	0.0	94.5
519	3.5	0.5	5.5	90.5
522	9.8	0.0	0.0	90.2
525	3.5	0.0	0.0	96.5
528	3.5	3.4	0.0	93.1

531	5.5	2.5	0.0	92.0
534	5.7	1.0	0.0	93.3
537	5.7	7.0	0.0	87.3
540	6.6	0.0	0.0	93.4
543	6.0	2.5	0.0	91.5
546	6.0	2.5	0.0	91.5
549	3.5	3.5	0.0	93.0
552	5.3	1.1	0.2	93.4
555	8.5	0.0	0.0	91.5
558	9.2	1.8	0.0	89.0
561	8.5	0.0	0.6	90.9
564	6.0	0.0	0.0	94.0
567	9.2	1.8	0.0	89.0
570	5.7	0.0	0.3	94.0
573	6.0	2.5	0.0	91.5
576	20.2	0.0	0.0	79.8
579	7.6	0.0	0.9	91.5
582	6.0	2.5	0.0	91.5
585	6.0	2.5	0.0	91.5
588	4.7	2.9	0.0	92.4
591	3.8	5.3	0.2	90.7
594	6.0	2.5	0.0	91.5

7.1.2 Internal Pillars

The internal pillars all suffered from the same segregation (Figure 51 to Figure 53) as the external pillars due to manufacture flaws, with the exception of the internal pillars, which do not have embedded rainwater pipes.

Figure 51: segregation due to manufacture flaws on Pillar 474 (private collection)

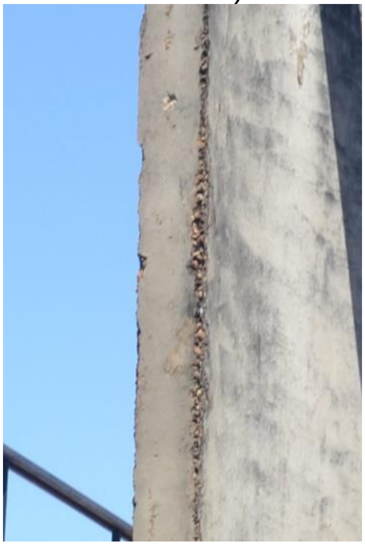


Figure 52: segregation due to manufacture flaws on Pillar 504 (private collection)

Figure 53: segregation due to manufacture flaws on Pillar 516 (private collection)

The difference between the two is that the internal pillars manifested more stains due to humidity (Figure 54 to Figure 56). Most likely due to the fact that the internal pillars do not receive as much sun and wind, they remain in contact with humidity for a longer period of time, causing the appearance of mould. These microorganisms affect the pillars' surface by producing black, brown or green stains.

Figure 54: stains due to humidity on Pillar 477 (private collection)

Figure 55: stains due to humidity on Pillar 516 (private collection)

Figure 56: stains due to humidity on Pillar 570 (private collection)

According to the GDE-UnB table, the Fp for stains is 0.60 and we considered the damage to be of an Fi of 0.50, or tolerable. However, since the defect only affects the structure's appearance, we considered the same defect to be minor according to the Dutch Standard, but with high intensity. The CS was then calculated according to the affected volume. The defects on the inner pillars were also mapped and their volume calculated, according to Table 8.

Table 8: Defect volume percentage within each internal pillar

	Pathology %			
Section	Manufacture Flaw	Stains	Reinforcement Corrosion	Remaining
474	1.6	24.3	0.0	74.1
477	1.7	24.2	0.0	74.1
480	2.4	12.5	0.0	85.1
483	3.6	13.9	0.0	82.5
486	3.2	4.3	0.0	92.5
489	1.9	4.3	0.0	93.8
492	1.9	11.8	0.0	86.3
495	3.2	4.3	0.0	92.5
498	1.6	24.3	0.0	74.1
501	1.7	24.2	0.0	74.1
504	2.4	12.5	0.0	85.1
507	3.6	13.9	0.0	82.5
510	3.2	4.3	0.0	92.5

513	1.9	4.3	0.0	93.8
516	1.9	11.8	0.0	86.3
519	3.2	4.3	0.0	92.5
522	3.2	80.0	0.0	16.8
525	0.3	24.5	0.0	75.2
528	3.6	50.0	0.0	46.4
531	1.9	13.2	0.0	84.9
534	1.5	13.2	0.0	85.3
537	0.3	24.5	0.0	75.2
540	1.7	24.4	0.0	73.9
543	1.2	4.2	0.0	94.6
546	3.6	50.0	0.0	46.4
549	2.9	51.0	0.0	46.1
552	2.9	51.0	0.0	46.1
555	2.9	13.2	0.0	83.9
558	3.6	50.0	0.0	46.4
561	17.8	42.2	0.0	40.0
564	17.8	42.2	0.0	40.0
567	4.3	42.2	0.0	53.5
570	3.6	13.2	0.0	83.2
573	3.6	13.2	0.0	83.2
576	3.6	13.2	0.0	83.2
579	1.2	4.3	0.0	94.5
582	1.0	8.9	0.2	89.9
585	2.9	51.0	0.0	46.1
588	1.2	4.3	0.0	94.5
591	1.0	8.9	0.2	89.9
594	3.6	13.2	0.0	83.2

7.1.3 T-Section Beams

Shortly after the building's construction, it was detected that the beams' upper surface needed additional coverage and so a layer of mechanical protection was added.

Figure 57: Removed mechanical protection and waterproofing between Beams 471 and 474 (private collection)

Figure 58: Removed mechanical protection and waterproofing between Beams 492 and 501 (private collection)

After almost 50 years, however, part of the mechanical protection has lost most of its waterproofing and some has even been removed (Figure 57 and Figure 58). The Fp thus indicated for deficient coverage in beams is 0.60 and the Fi, 0.75.

Subsequently, according to the Dutch Standard, the same defect is considered serious with high intensity.

The beam ends toward the internal pillars (Figure 59 and Figure 60) are also affected by humidity, causing mould and stains.

Figure 59: T-beam ends toward the internal pillars – section 516 (private collection)

Figure 60: T-beam ends toward the internal pillars – section 588 - 594 (private collection)

The defects on the inner pillars were also mapped and their volume calculated, as you can see in Table 9.

Table 9: Defect volume percentage within each T-section beam

	Pathology %		
Section	Deficient Coverage	Stains	Remaining
474	2.0	8.3	89.7
477	0.0	8.3	91.7
480	0.0	8.3	91.7
483	2.0	8.3	89.7
486	0.1	8.3	91.6
489	0.2	8.3	91.5
492	0.8	8.3	90.9
495	0.8	8.3	90.9
498	1.0	8.3	90.7
501	1.0	8.3	90.7
504	0.0	8.3	91.7
507	0.0	8.3	91.7
510	1.5	8.3	90.2
513	0.0	8.3	91.7
516	0.0	8.3	91.7
519	0.0	8.3	91.7
522	0.0	8.3	91.7
525	0.1	8.3	91.6
528	0.1	8.3	91.6
531	0.0	8.3	91.7
534	0.0	8.3	91.7
537	0.0	8.3	91.7
540	0.5	8.3	91.2
543	0.0	8.3	91.7

546	0.0	8.3	91.7
549	0.0	8.3	91.7
552	0.0	8.3	91.7
555	0.0	8.3	91.7
558	0.0	8.3	91.7
561	0.0	8.3	91.7
564	0.0	8.3	91.7
567	0.0	8.3	91.7
570	0.0	8.3	91.7
573	0.0	8.3	91.7
576	0.0	8.3	91.7
579	0.0	8.3	91.7
582	0.0	8.3	91.7
585	0.0	8.3	91.7
588	0.0	8.3	91.7
591	0.0	8.3	91.7
594	2.1	8.3	89.6

7.1.4 Gutter Beams

All the sections of gutter beams showed relatively the same percentage of efflorescence and stains (Figure 61 and Figure 62), both of which were discussed in previous sections.

Figure 61: Efflorescence and stains between sections 480 and 483 (private collection)

Figure 62: Efflorescence and stains between sections 585 and 591 (private collection)

7.1.5 Square-Section Beams

The square-section beams are similarly affected by mould and stains due to high humidity, as seen in Figure 63 and Figure 64.

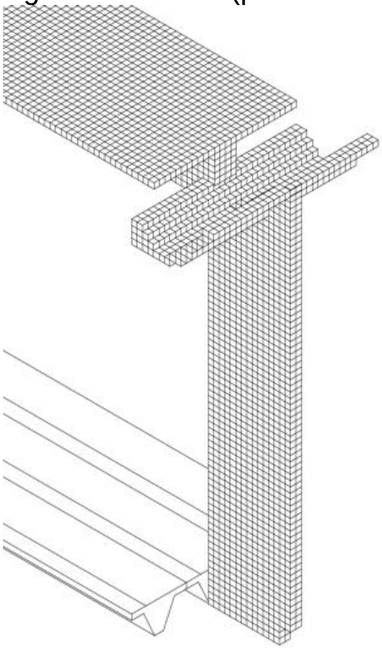
Figure 63: mould and stains between sections 474 and 477 (private collection)

Figure 64: mould and stains between sections 579 and 582 (private collection)

7.2 DIGITAL MAPPING

In order to estimate the volume of each defect within each structural element, the elements were subdivided using the finite element method in Grasshopper, creating a grid of 10x10x10cm (Figure 65). For this purpose, an open source Grasshopper plug-in was chosen, Aaron Porterfield's Crystallon v1.0, whose *Voxelize* command allows the generation and modification of a set of voxels used to populate a lattice structure with unit cells. The grid size was chosen according to available computer processing abilities and will need to be improved in subsequent studies. Each voxel was then assigned a CS (Condition Status) according to the detected defect, which is represented by Figure 67, Figure 68 and Figure 69.

Figure 65: voxels (private collection)



Visual inspection and photographic evidence were used to subdivide and map each element according to the found pathologies. Each voxel was thus given a CR (Condition Rating) value in agreement with the presence of a defect, its importance, intensity and the affected volume within each element, as exemplified by Figure 66.

Figure 66: Mapping of current status according to Dutch Standard Condition Rating for each defect – Pillars 498 to 519 (private collection)

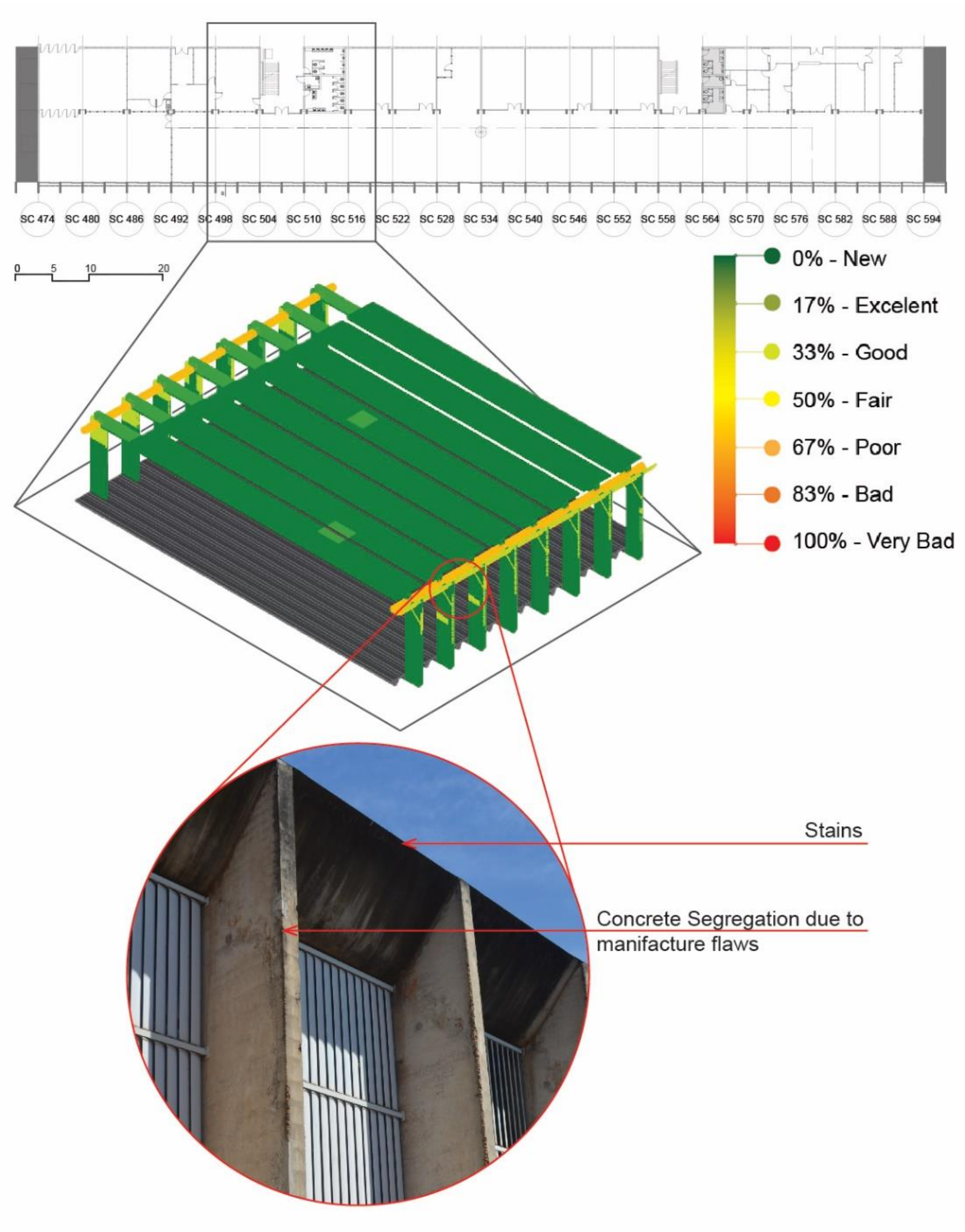


Figure 67: Mapping of current status according to Dutch Standard Condition Rating – Pillars 474 to 495 (top) and 498 to 519 (bottom) (private collection)

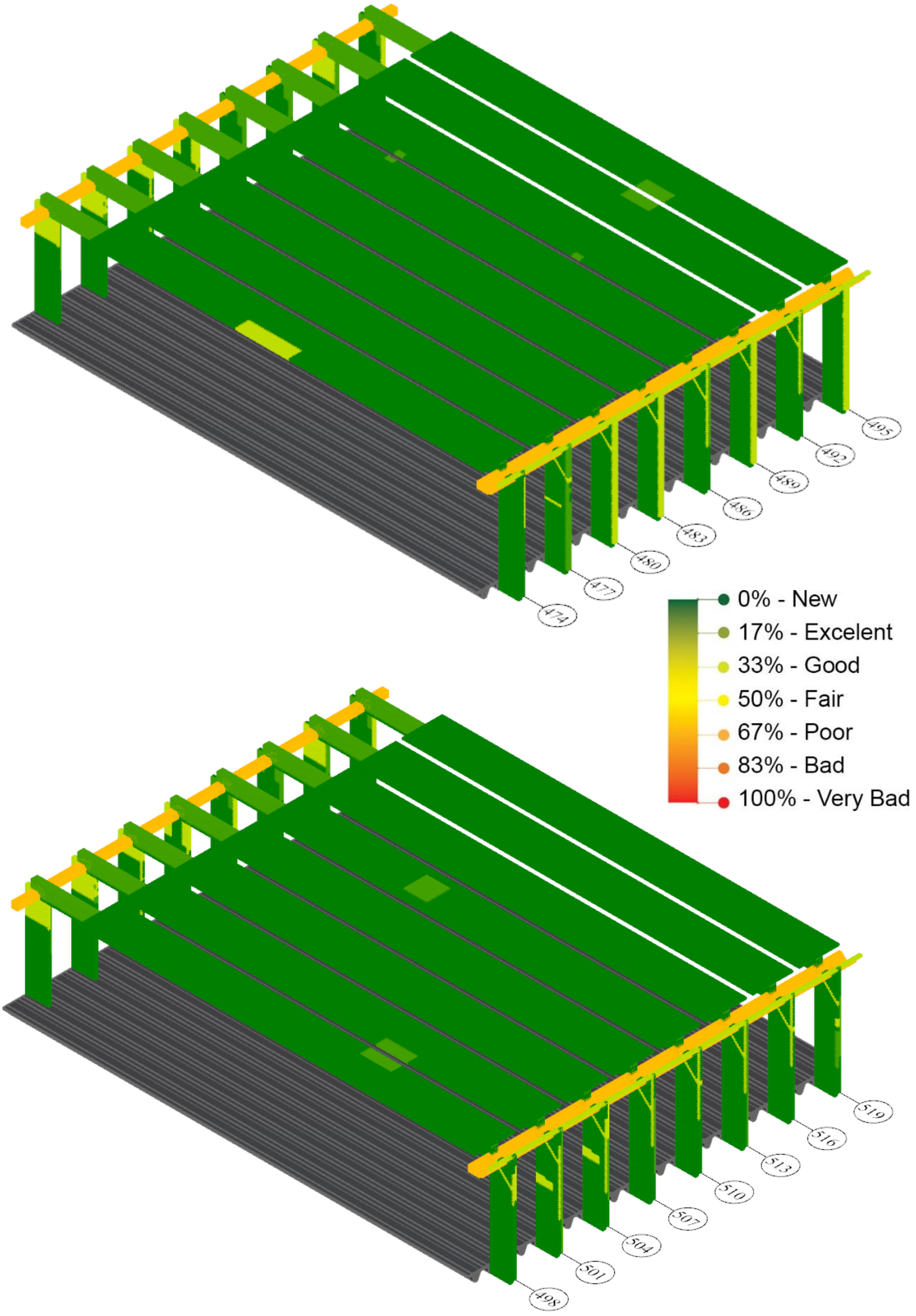


Figure 68: Mapping of current status according to Dutch Standard Condition Rating – Pillars 522 to 543 (top) and 546 to 567 (bottom) (private collection)

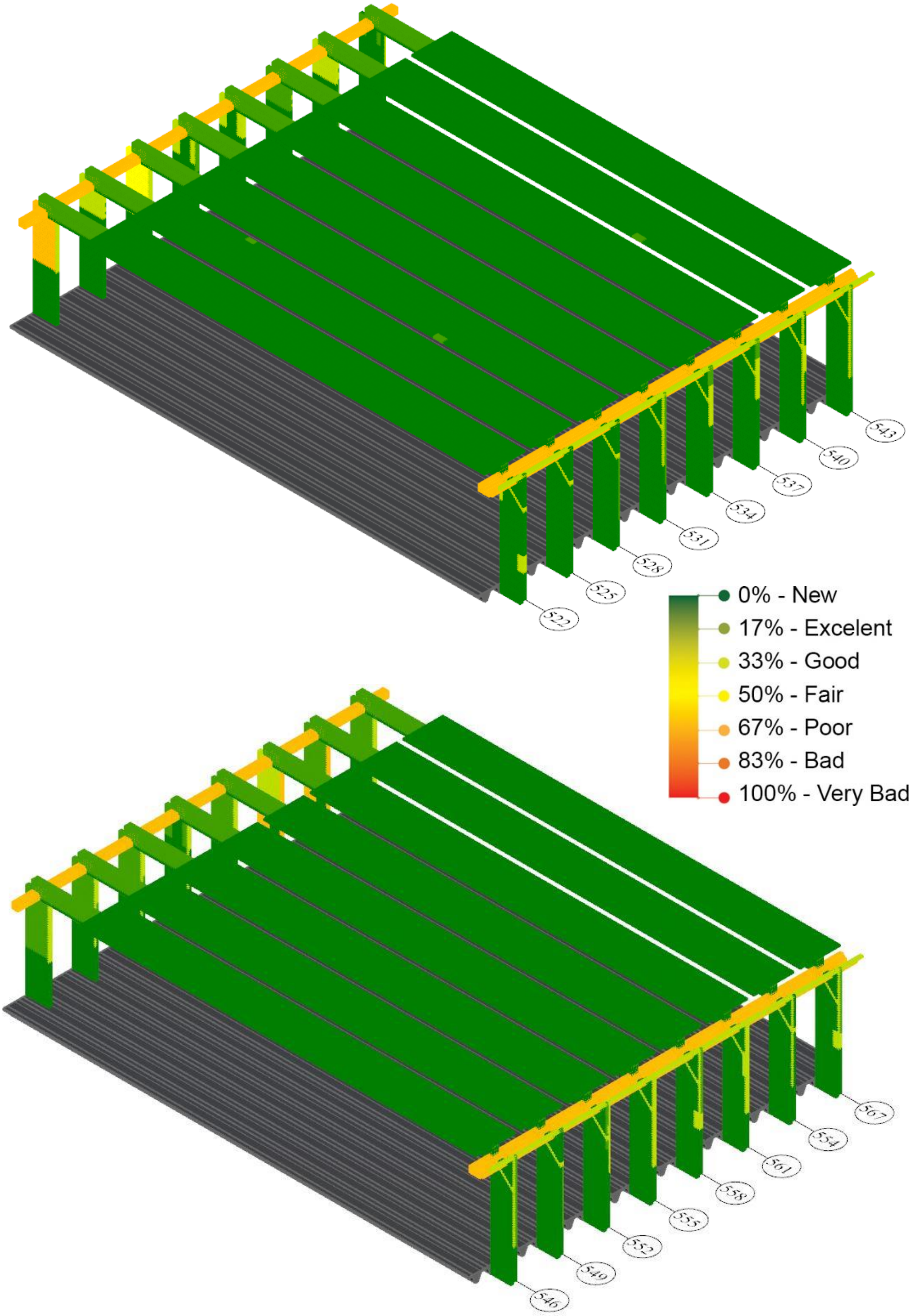
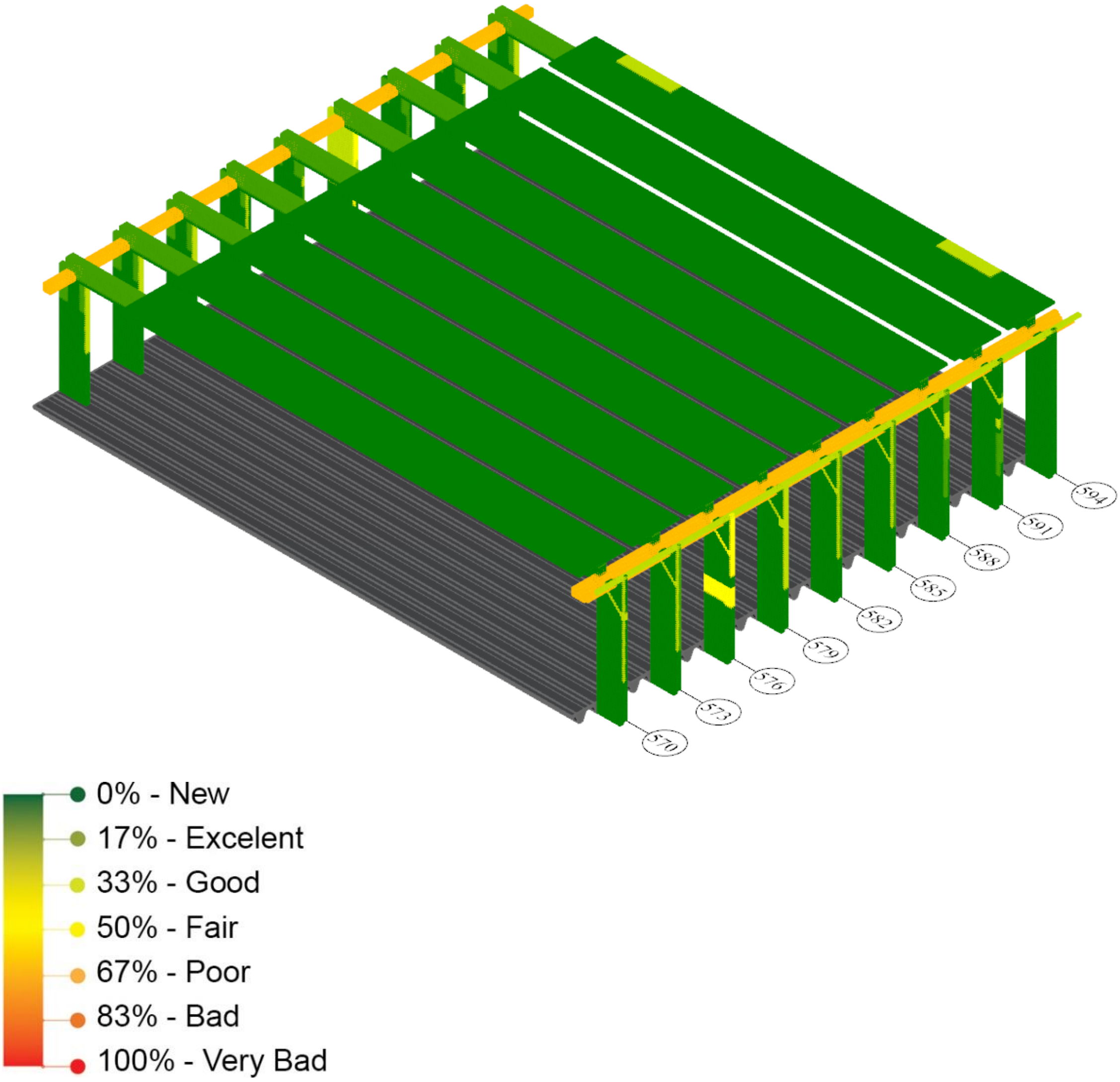


Figure 69: Mapping of current status according to Dutch Standard Condition Rating – Pillars 570 to 594 (private collection)



7.3 SCRIPTING, COMPARISON AND ANALYSIS OF DIFFERENT DEGRADATION AND DEPRECIATION METHODS

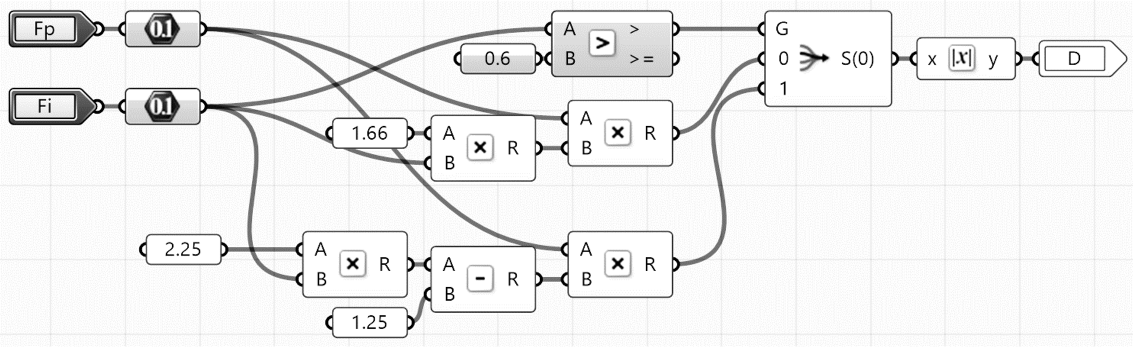
7.3.1 GRASSHOPPER ALGORITHMS

All of the methods used had to be scripted into Grasshopper. Grasshopper is a graphical algorithm editor, a visual programming language and a digital environment that can be integrated, through a plug-in, to the Rhinoceros 3D computer-aided design application. The algorithms are created by dragging parameters and components into a canvas. Parameters are basically containers of either geometry, such as points, curves, surfaces or *breps* (boundary representations), or data, such as integer, number, text or colour. Geometry containers must be linked to pre-constructed geometry within Rhino, while data containers can be set manually or generated using components. Components, on the other hand, allow you to construct new data or geometry from a set of inputs.

7.3.1.1 Parametric GDE-UnB

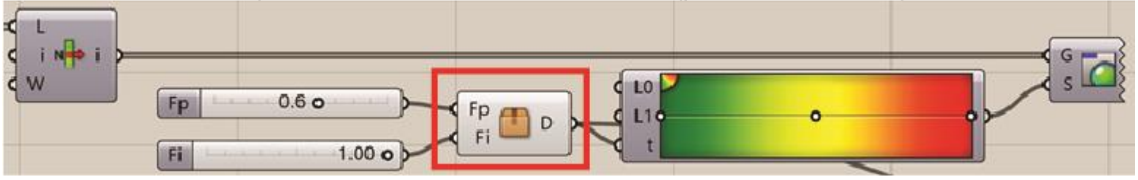
One of the most used Grasshopper function for this research was the ability to cluster components, or group a set of functions into a single container. An example of a cluster is shown in Figure 70. This cluster represents the Tuutti line chart, for which it was necessary to indicate the cluster input values, Fp and Fi, and output value, D, in order to group it into a cluster.

Figure 70: Tuutti cluster (private collection)



The entire Tuutti cluster was merged into one single container, as shown in Figure 71, where the inputs are assigned through a number slider and the output is the damage value for each group of damaged voxels.

Figure 71: Tuutti cluster container (private collection)



The G_{de} formula was also clustered, as shown in Figure 72, where all damage values (D's) obtained for a single structural element are inputted into the algorithm, which generates a G_{de}.

Figure 72: G_{de} cluster (private collection)

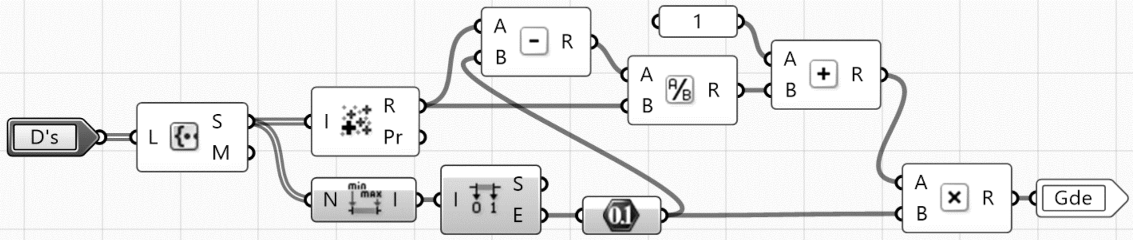
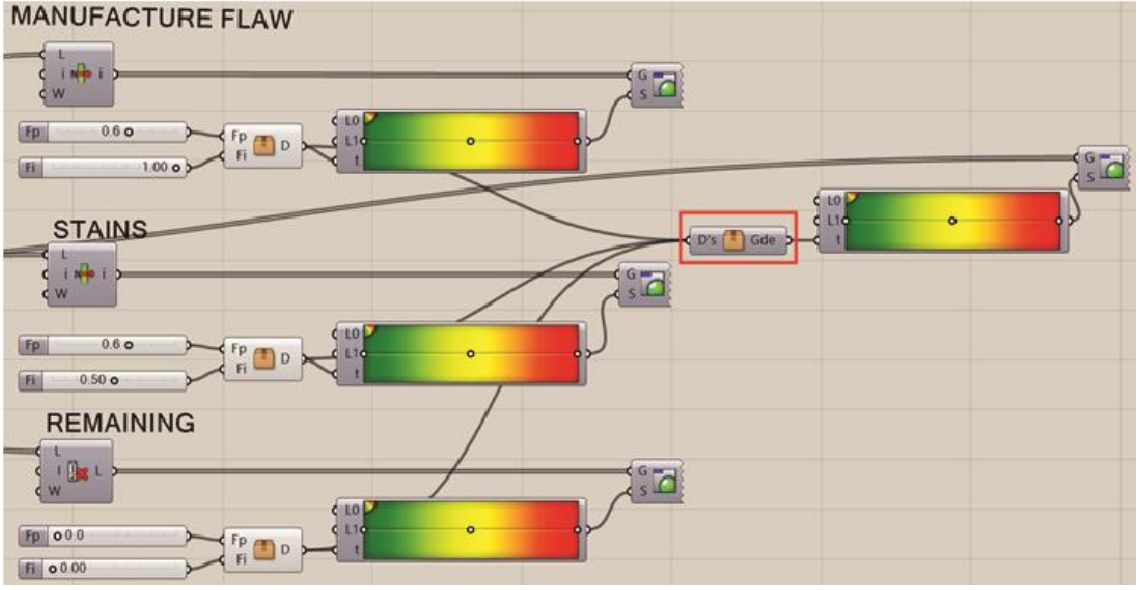


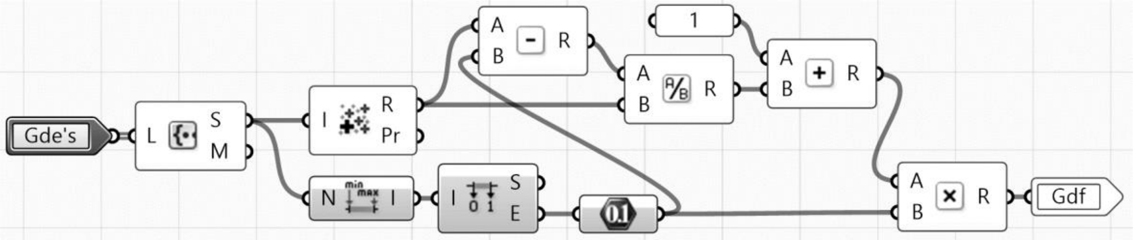
Figure 73 shows the G_{de} cluster in a single container, receiving data from the damage degrees calculated for each pathology.

Figure 73: G_{de} cluster container (private collection)



The last cluster created for the GDE-UnB was the G_{df}, which determines the deterioration degree for a family of structural elements (Figure 74).

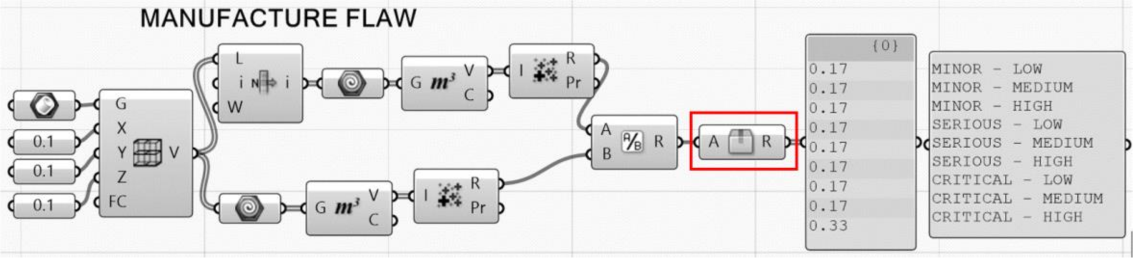
Figure 74: G_{df} cluster (private collection)



7.3.1.2 Dutch Standard

Unlike the GDE-UnB method, the Dutch Standard takes into consideration the affected volume of each pathology. Therefore, the volume of each mapped pathology was divided by the volume of the respective structural element, as seen in Figure 75.

Figure 75: volume calculation of each pathology: volume calculation of each pathology (private collection)

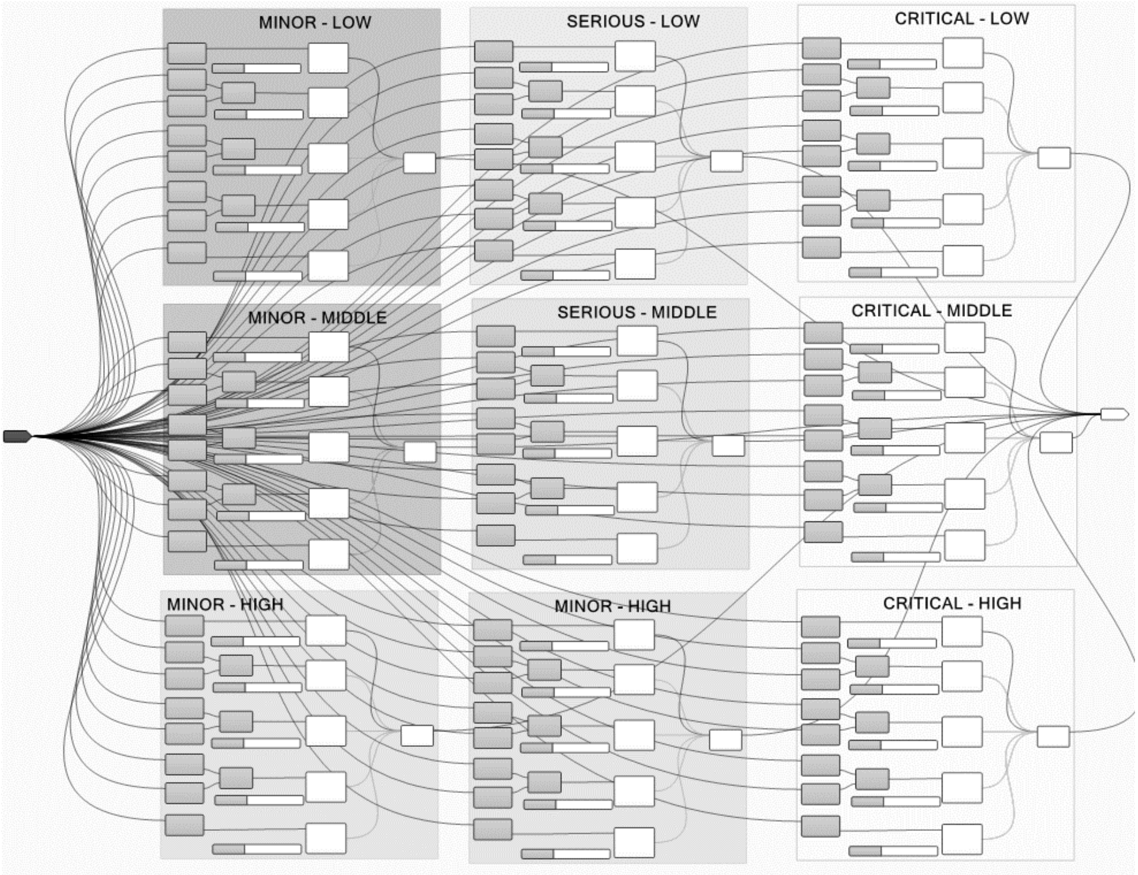


```
0.17
0.17
0.17
0.17
0.17
0.17
0.17
0.17
0.33
```

```
MINOR - LOW
MINOR - MEDIUM
MINOR - HIGH
SERIOUS - LOW
SERIOUS - MEDIUM
SERIOUS - HIGH
CRITICAL - LOW
CRITICAL - MEDIUM
CRITICAL - HIGH
```

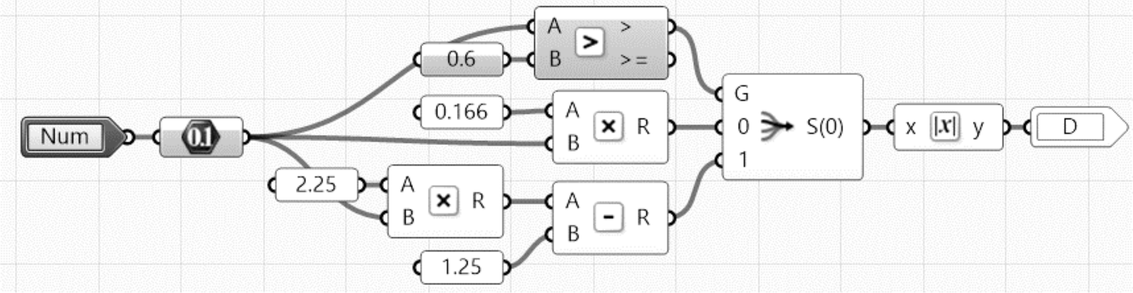
The highlighted cluster is shown in Figure 76 and combines the estimation of nine different CR values, one for each level of importance and intensity for the volume percentage resulted from the previous algorithm.

Figure 76: CR calculation cluster (private collection)



The resulting CR, chosen from the given list of CR values, was then inputted into an adapted Tuutti formula (Figure 77), which in turn supplied a D value, which again was inputted into the existing G_{de} cluster (Figure 73). Finally, the detected G_{de} was inputted into the Ross-Heidecke formula to calculate the kie, kif and kg.

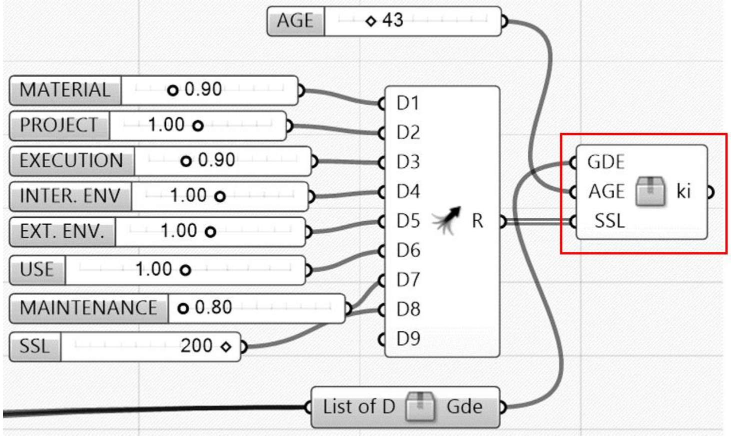
Figure 77: Tuutti formula adapted for Dutch Standard CR value (private collection)



7.3.1.3 Ross-Heidecke

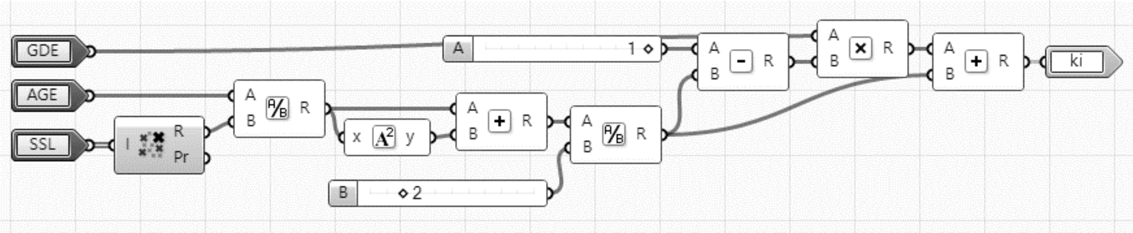
On-site physical inspection and historical research allowed us to roughly quantify Pereira's (2013) characteristic's quality for each chosen parameter. Based on the factorial method proposed by ISO 15.686, Pereira argues that it is necessary to assign a factor from 0.8 (non-existent or very bad) to 1.2 (excellent), and multiply it by the SSL to establish the ESL. These factors were programmed into Grasshopper according to Figure 78 and inputted into the highlighted cluster (Figure 79).

Figure 78: Pereira's contribution to the Ross-Heidecke method programmed in Grasshopper. (private collection)



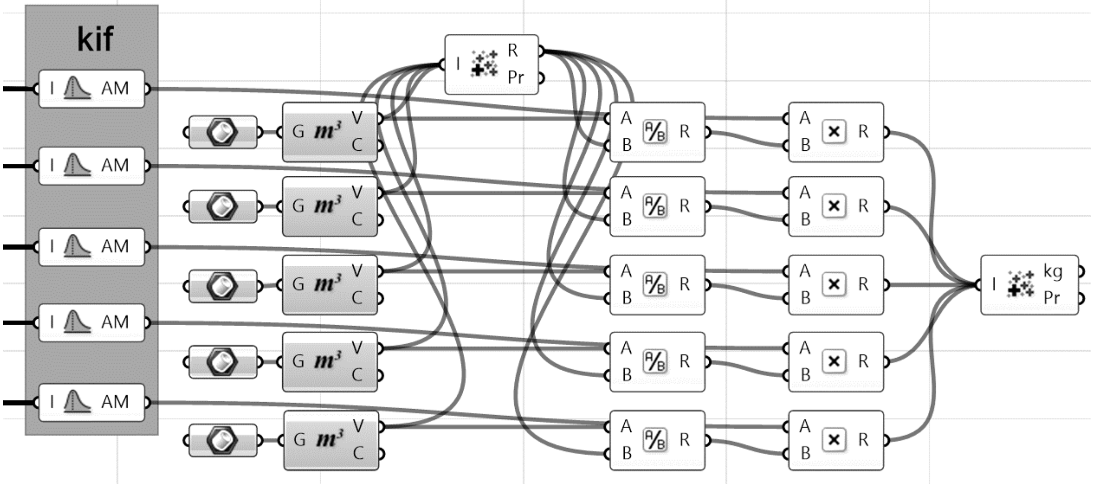
We then programmed the initial Ross-Heidecke formula into Grasshopper, however, instead of attributing a Depreciation Status according to damage level, we inputted the individual G_{de} for each element, as shown in Figure 79, which resulted in an kie.

Figure 79: Ross-Heidecke method programmed in Grasshopper for different beam damage levels. (private collection)



Since the structure was completely pre-fabricated, all elements within a specific family are worth the same. Therefore, in order to calculate each element family's kif, a simple average of all belonging kie's was sufficient. Grasshopper was then programed to calculate the weight of each section according to the relation between each individual volume to the total volume. The weighted average of the kif's, in turn provided the kg (Figure 80).

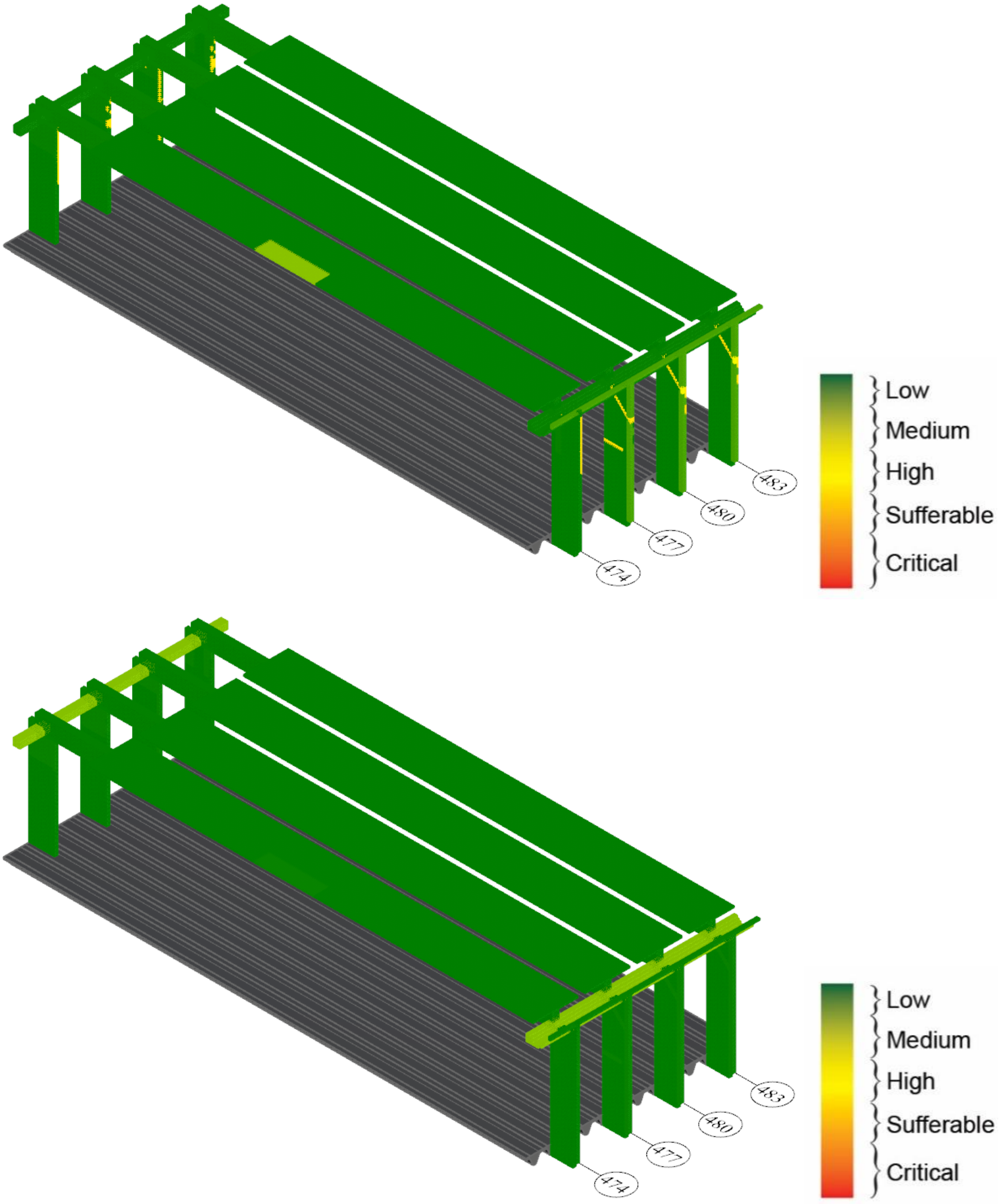
Figure 80: Pimenta's contribution to the Ross-Heidecke method programmed in Grasshopper. (private collection)



7.4 GDE-UnB vs. Dutch Standard

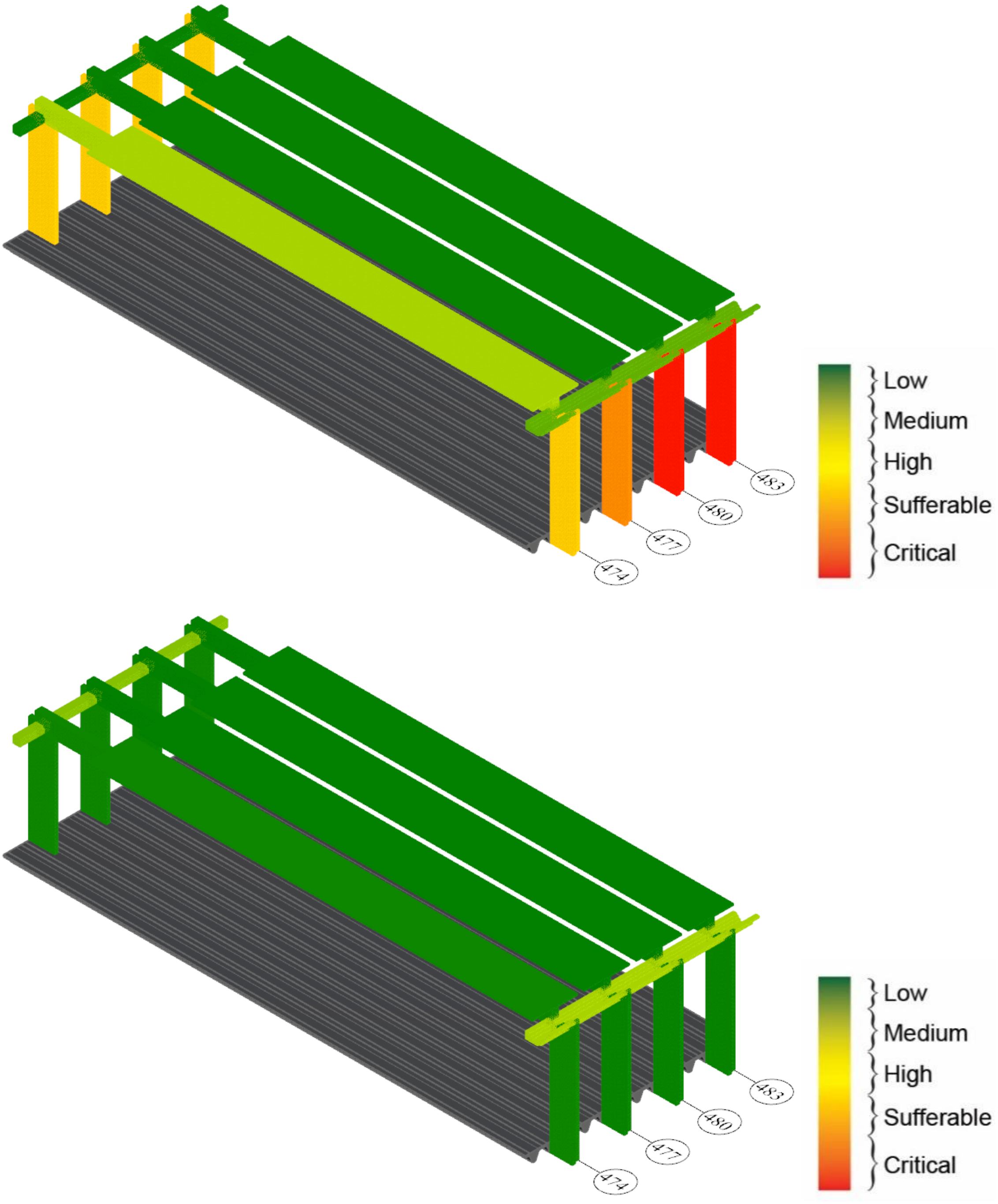
In order to determine which deterioration method would be more appropriate for incorporation into the Ross-Heidecke depreciation method, it was necessary to compare the parametric GDE-UnB with the parametric Dutch Standard. For this purpose, a section of four structural sets were chosen, starting at pillars 474 to 483. The same inspection was used for both methods, differing only the Condition Rating of the Dutch Standard and the importance and ponderation factors of the GDE-UnB method. The methods were then compiled and the G_{de} formulas for damage distribution (D) and deterioration degrees (G_{de} and G_{df}) were calculated for both the GDE-UnB and the Dutch Standard (Figure 81, Figure 82 and Figure 83).

Figure 81: top: D for GDE-UnB according to Tutti method; bottom: D for the Dutch Standard according to an adaptation of the Tutti method



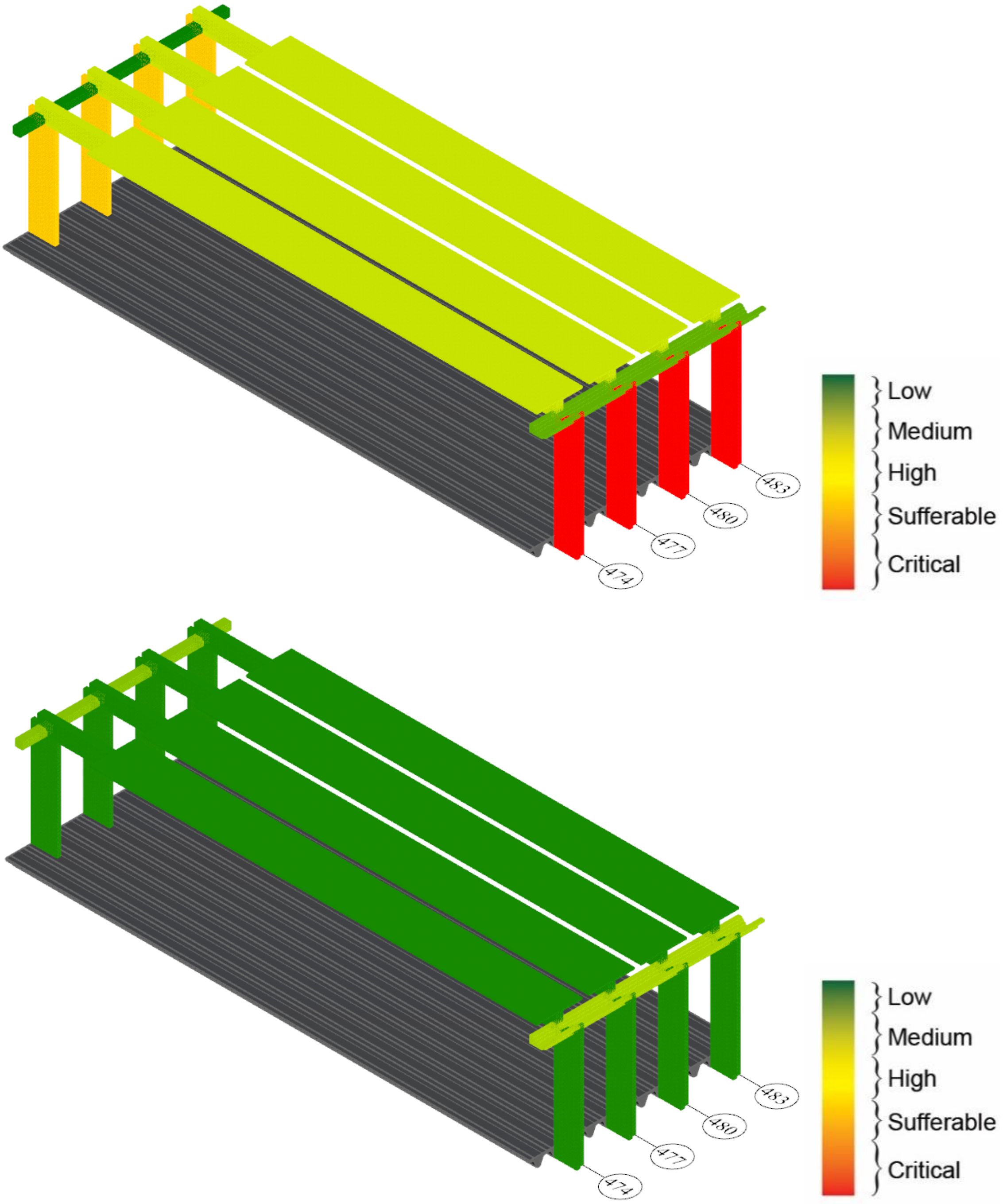
The visual difference becomes clear when the G_{de} for each element is calculated. Due to the fact that the worse defects affect only a small part of each element and the Dutch Standard takes into account the affected volume, it is possible to see that the G_{de} according to the Dutch Standard amounts to far less than the GDE-UnB (Figure 82).

Figure 82: left: G_{de} for GDE-UnB; right: G_{de} for Dutch Standard



With the G_{df} (deterioration degree for each family of elements) calculation, the difference is even greater. While the G_{df} according to the GDE-Unb (Figure 83) is considered critical or high for all pillars, when considering the affected volume, it can be said that the Dutch Standard represents a more realistic approach.

Figure 83: left: G_{df} for GDE-UnB; right: G_{df} for Dutch Standard



Through the visual analysis of both the parametric GDE-UnB and the parametric Dutch Standard, the importance of taking the volume of pathologies into consideration is evident. The deterioration degree calculated with the GDE-UnB without element discretisation is much more critical than the Dutch Standard and clearly does not represent reality. Furthermore, the GDE-UnB formula puts too much weigh on the highest deterioration factor, without considering that the affected area might be minimal and not relevant to the remaining structure.

The ideal method is therefore a combination of the two methods. While it is better to calculate the CR according to the Dutch Standard, as it takes into consideration the volume of pathologies, the CR must then be processed within the parametric GDE-UnB formulas in order to obtain a G_{de}.

7.5 Current Status according to proposed methodology

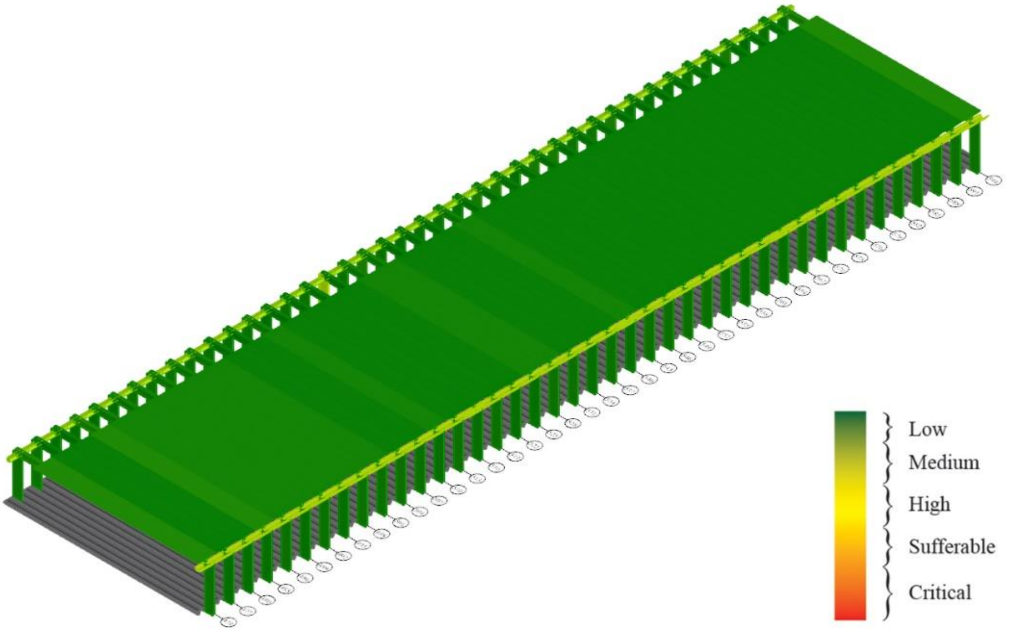
The ICC was analysed according to the proposed hybrid method. First, the elements and their defects were mapped and each defect was given a CR according to the parametric Dutch Standard. The CR was then inputted into an adapted Tuutti formula in order to supply a D, which in turn was used to calculate a G_{de} for each element. This G_{de} was therefore used to substitute the CS within the Ross-Heidecke method to calculate the respective kie, kif and kg.

7.5.1 Resulting Deterioration Degrees According to the Dutch Standard + GDE-UnB

When it came to calculating the D for the GDE-UnB method, instead of attributing the traditional importance and ponderation factors, we used the current status according to the Dutch Standard. The D of each voxel was thus calculated according to the previously mentioned adapted Tuutti Method.

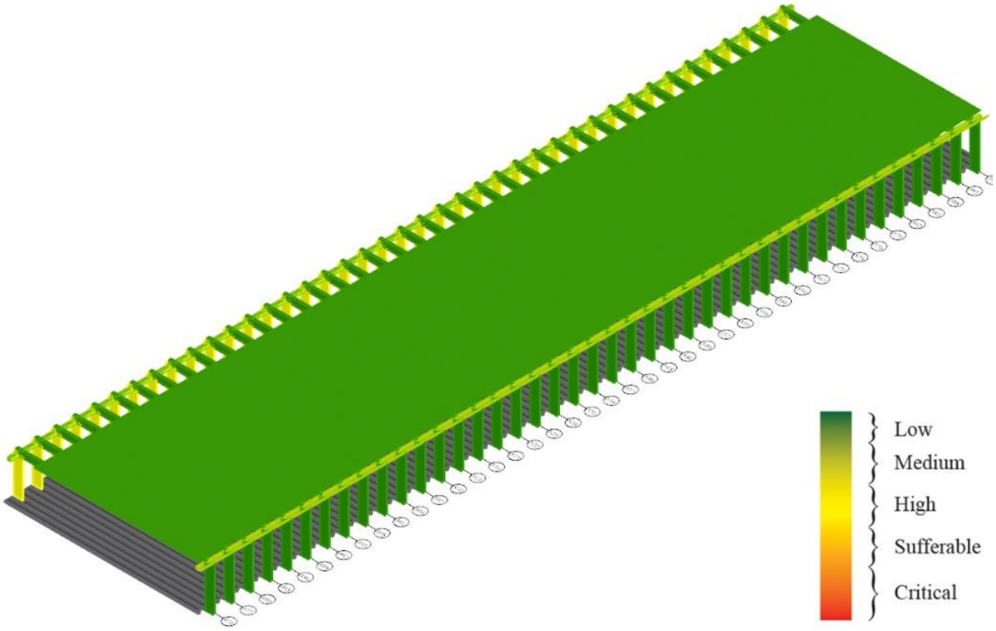
The D was then inputted into the traditional GDE-UnB formula in order to calculate the resulting G_{de} for each individual element (Figure 84).

Figure 84: G_{de} (private collection)



The G_{df} for each element family (Internal Pillars, External Pillars, T-section Beams, Square-section Beams and Gutter Beams) was calculated according to GDE-UnB formula and is shown in Figure 85.

Figure 85: G_{df} (private collection)

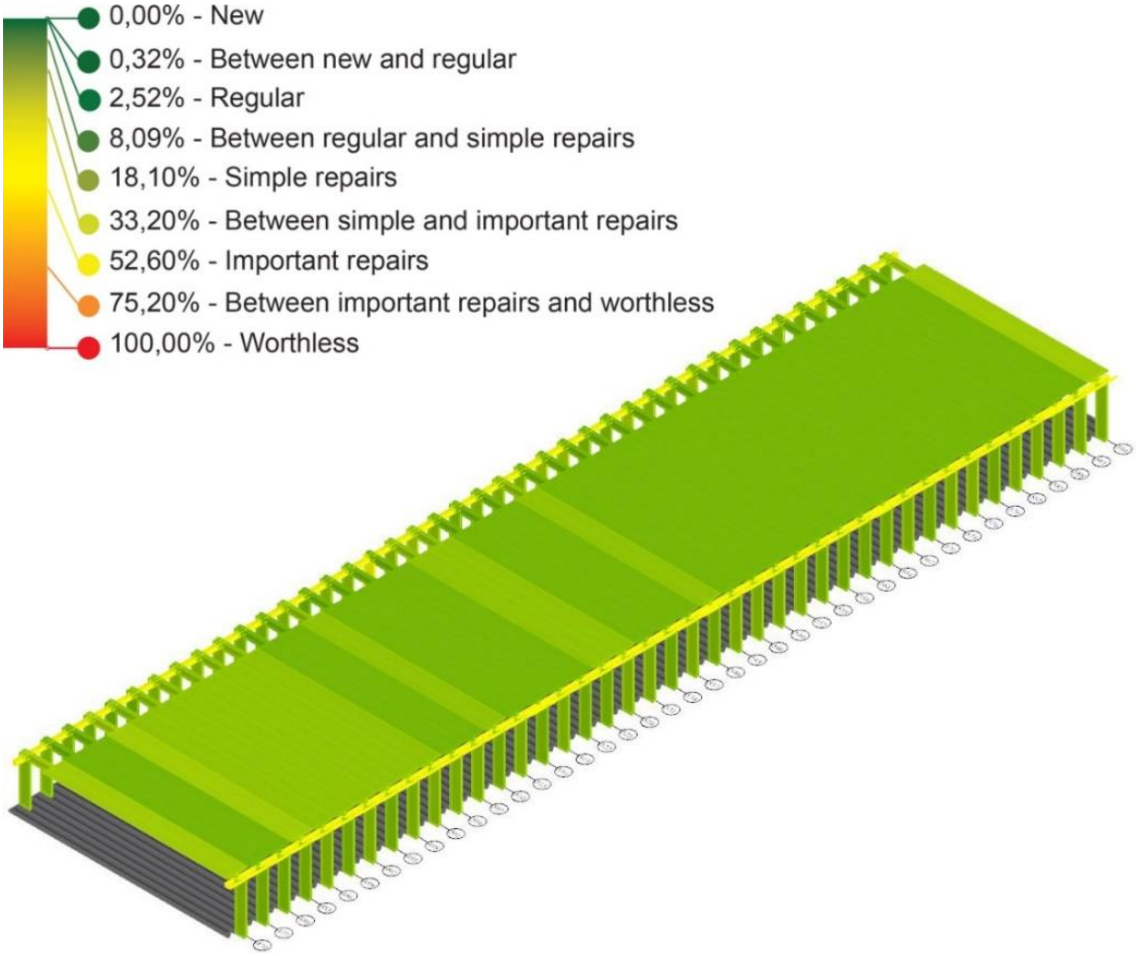


7.5.2 Ross-Heidecke Depreciation Factors through the Hybrid Method

The G_{de} acquired through the combination of the parametric Dutch Standard and parametric GDE-UnB was used to calculate a kie for each element, represented in Figure 86. The ESL used was calculated as approximately 130 years and the factors used to determine it were:

- SSL = 200 years
- Material = 0.9
- Project = 1.0
- Execution = 0.9
- Interior Environment = 1.0
- Exterior Environment = 1.0.
- Use = 1.0
- Maintenance = 0.8

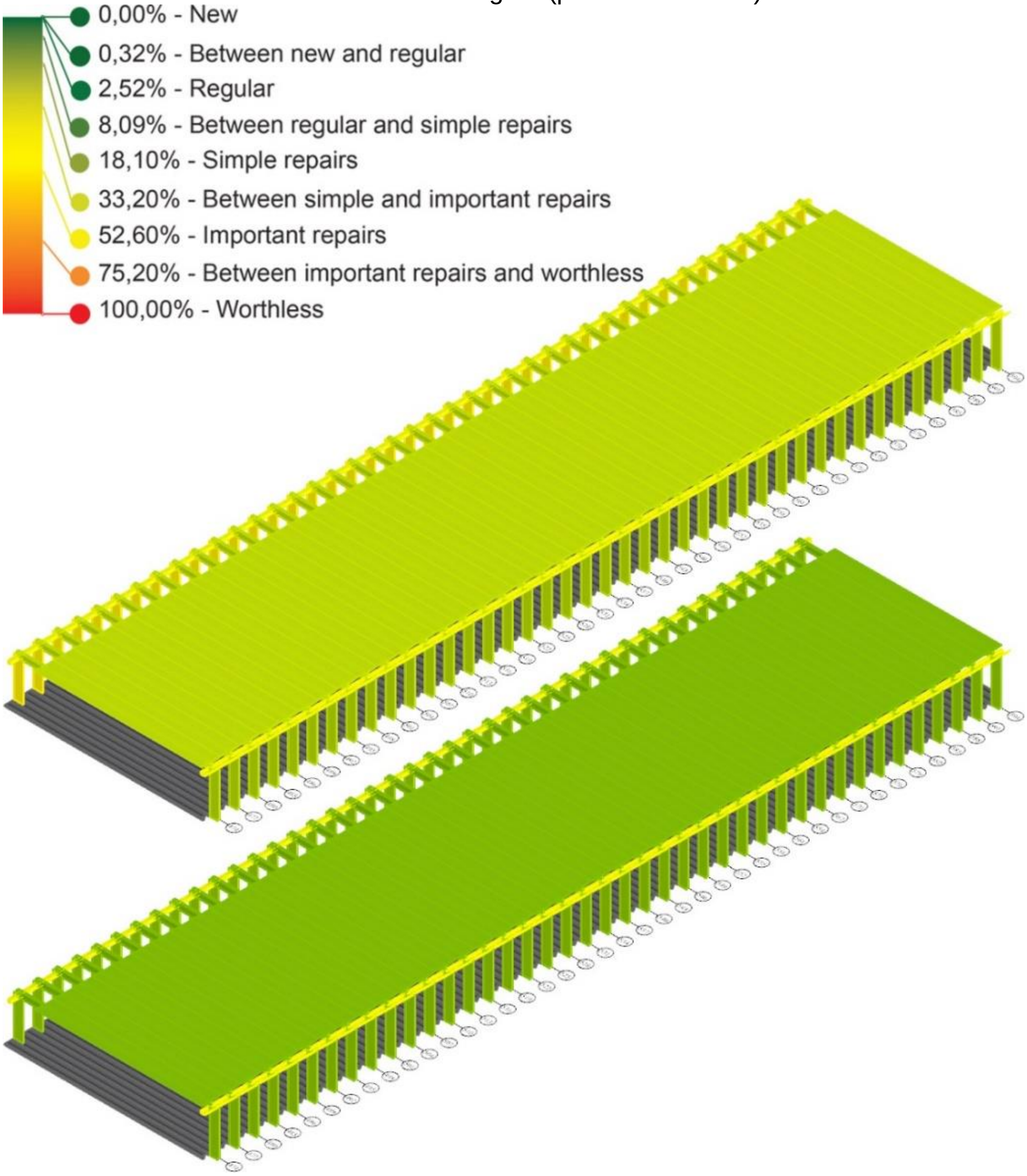
Figure 86: kie for each element (private collection)



At this point it was necessary to decide if the kif should be calculated from the average of individual kie's or from the G_{df}. Both were calculated and contrasted, as shown in Figure 87. For a kif calculated from the average of all kie's, the results were the following: internal pillars – 0.28; external pillars – 0.27; t-section beams

– 0.26; square-section beams – 0.42 and gutter beams – 0.46. On the other hand, the results of the kif’s based on the G_{df} were: internal pillars: internal pillars – 0.59; external pillars – 0.32; t-section beams – 0.34; square-section beams – 0.42 and gutter beams – 0.46.

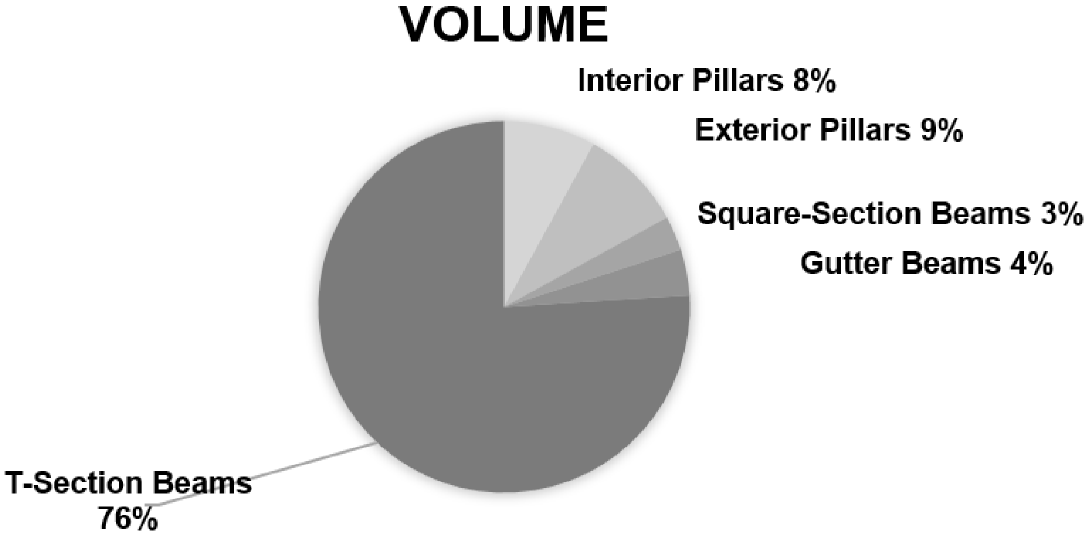
Figure 87: Uppermost image – kif calculation based on the G_{df}. Bottomost image - kif based on kie averaged. (private collection)



It thus became clear that, when calculating the kif based on the G_{df}, the presence of one or a few elements with a higher deterioration degree would have too great an impact on the depreciation factor. Since it would be incorrect to say that one completely deteriorated element does not diminish the entire building value, it was decided that the kif would be better calculated according to the average of all kie's.

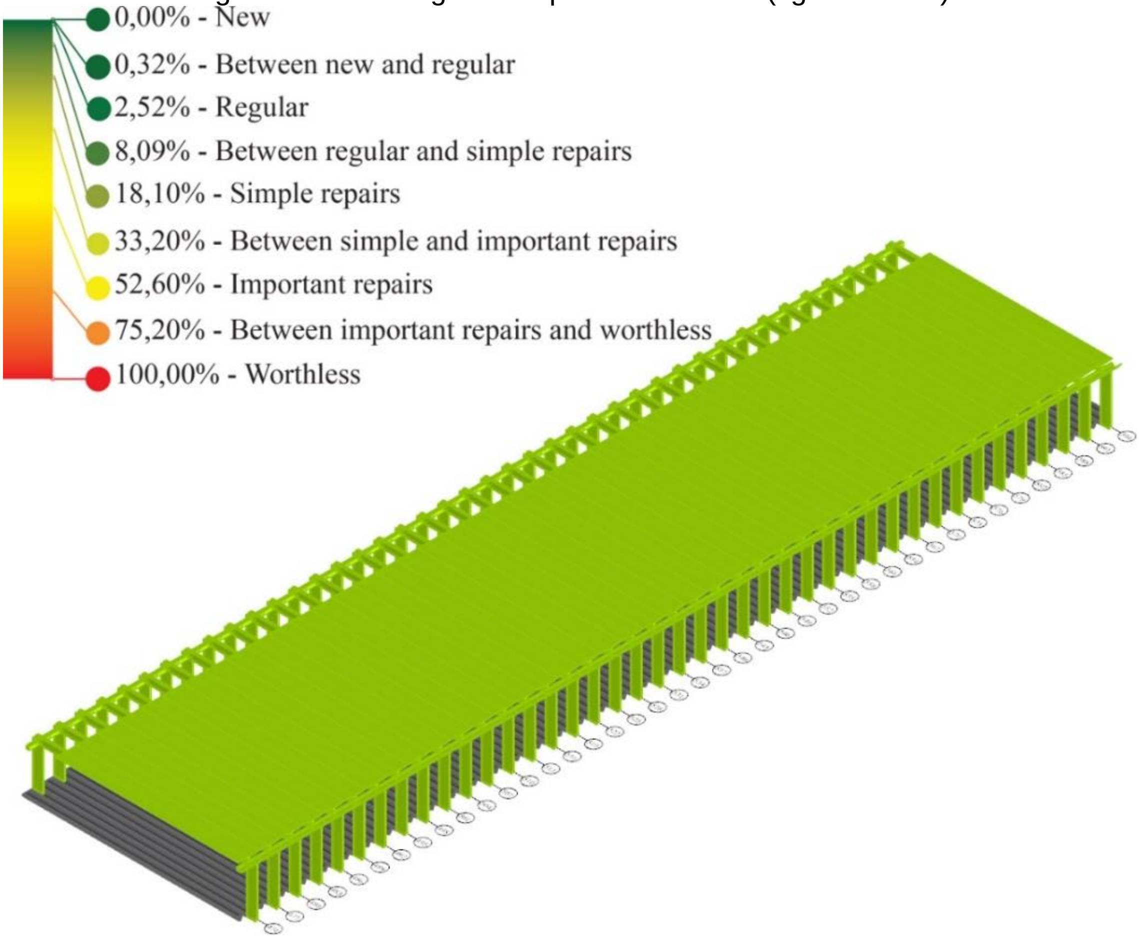
In order to verify the structure's global depreciation factor, it was necessary to assign a weigh to each family (Figure 88). As mentioned previously, since all elements are pre-fabricated reinforced or pre-stressed concrete, it was estimated that they all have approximately the same value per meter cubed. Therefore, the weight was established according to the volume of each family in relation to the entire structure.

Figure 88: Pie chart representing the volume of each element family within the chosen structural elements (private collection)



The weighted mean of all kif's was then used to determine a kg of approximately 27% (Figure 89).

Figure 89: current global depreciation factor (kg = 27.31%)



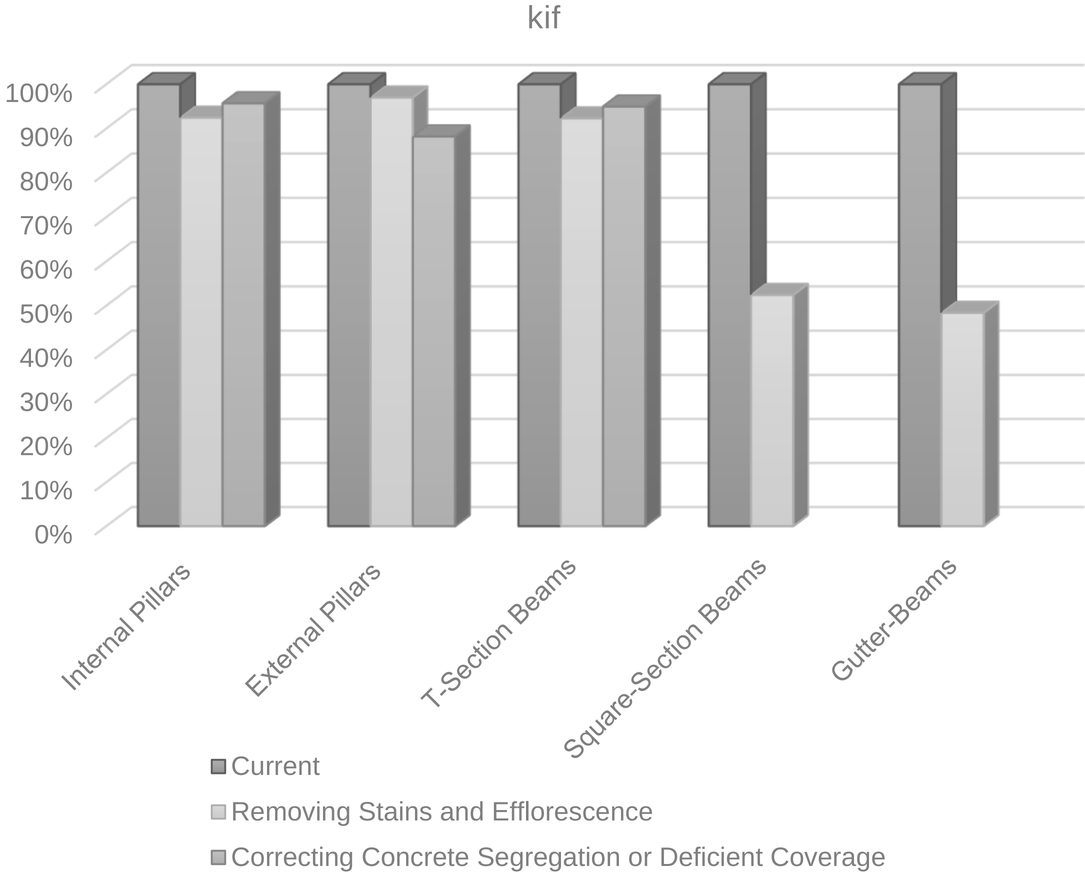
7.6 Scenario Simulation

Once the Grasshopper model was completed, it became possible to predict scenarios according to differentiated input values. Initially, different maintenance decisions, such as the removal of stains and efflorescence or the correction of concrete segregation and deficient coverage, were rapidly tested according to the impact on the deterioration degree and family and global depreciation factors. Then, the structure’s depreciation was analysed over time according to different types of deterioration progressions.

7.6.1 Maintenance Decision Scenarios

Two main decision scenarios were chosen and their impacts on the G_{df}, kif and kg calculated for each element family. The first scenario simulated the decision to remove stains and efflorescence from all elements within each family and the second, the decision to correct concrete segregation also on elements within each family (Figure 90).

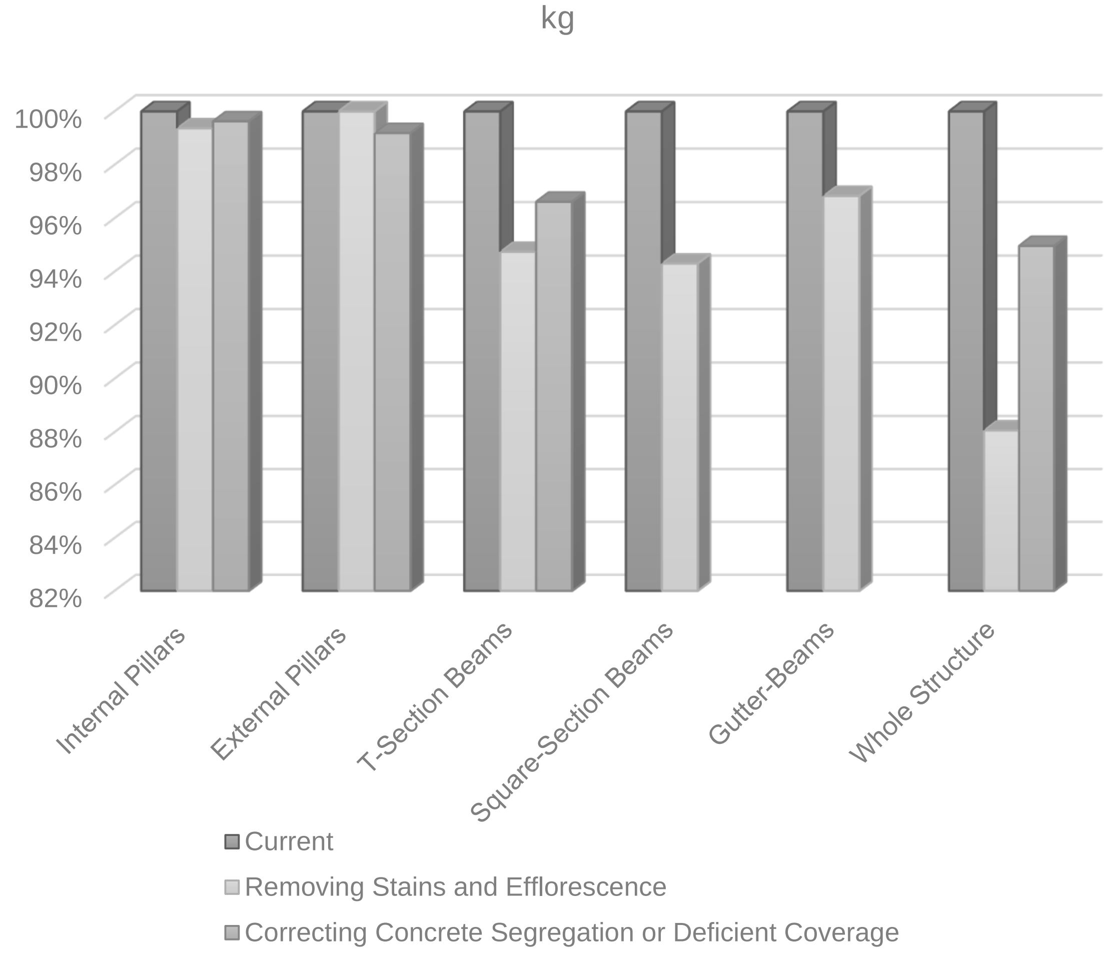
Figure 90: kif impacts for each scenario simulation (private collection)



From this simulation, it became clear that the financial value of each family, with the exception of the external pillars, would benefit more from the decision to remove all stains and efflorescence than from the decision to correct concrete segregation or deficient coverage.

The difference between each decision is even greater when considering the impact on the global depreciation factor of the entire structure, which had an initial value of 0.2724. Figure 91 demonstrates the impact on the global depreciation factor of removing stains and efflorescence from only the internal pillars (kg = 0.2707), only the external pillars (kg = 0.2723), only the t-section beams (kg = 0.2581), only the square-section beams (kg = 0.2569), only the gutter beams (kg = 0.2638) and from the entire structure (kg = 0.2399). It also demonstrates the impact of correcting concrete segregation and deficient coverage of only the internal pillars (kg = 0.2714), only the external pillars (kg = 0.2702), only the t-section beams (kg = 0.2632) and of the entire structure (kg = 0.2587)

Figure 91: kg impacts of each scenario simulation (private collection).



7.6.2 Depreciation Progressions

The second type of simulation was chosen to visually analyse how possible deterioration progressions would affect individual, family and global depreciation factors. Initially, a scenario was created to represent the depreciation rate if all defects were corrected and all G_{de}'s returned to zero. This scenario became the control group, a standard of comparison to which all posterior depreciation simulations will be compared. The chosen deterioration rates are mere hypothesis and years of observation and registration would be necessary to determine more accurate deterioration rates.

Afterwards, two types of deterioration rates were simulated, one with a modest deterioration rate and a worst case scenario.

7.6.2.4 Simulation 01

The first took into consideration a geometric progression of the deterioration rate in which all defect volume doubles every ten years. This simulation, however, does not consider that lesser defects can generate more important defects. Therefore, since most defects are either minor or serious, the service life is not very affected.

When comparing this scenario to the control group (Figure 92 and Figure 93), we can analyse that, even though the deterioration progress speeds up over time, there isn’t much difference between the time it takes to reach the structure`s complete depreciation.

In Figure 93, it is possible to globally compare the simulations between the depreciation rates of the control group and the first simulation. The control group starts with its current age of 43 years and removing each and every defect, the current kg would amount to 0.22. It will increase to 0.29 in 10 years’ time (2028), 0.36 in 20 years’ time (2038), 0.44 in 30 years’ time (2048), 0.53 by 2058, 0.62 by 2068, 0.71 by 2078, 0.82 by 2088 and 0.93 by 2098. It will reach the end of its service life in 2105.

Figure 92: Comparison between control group (left) and the first simulation (right) (personal collection)

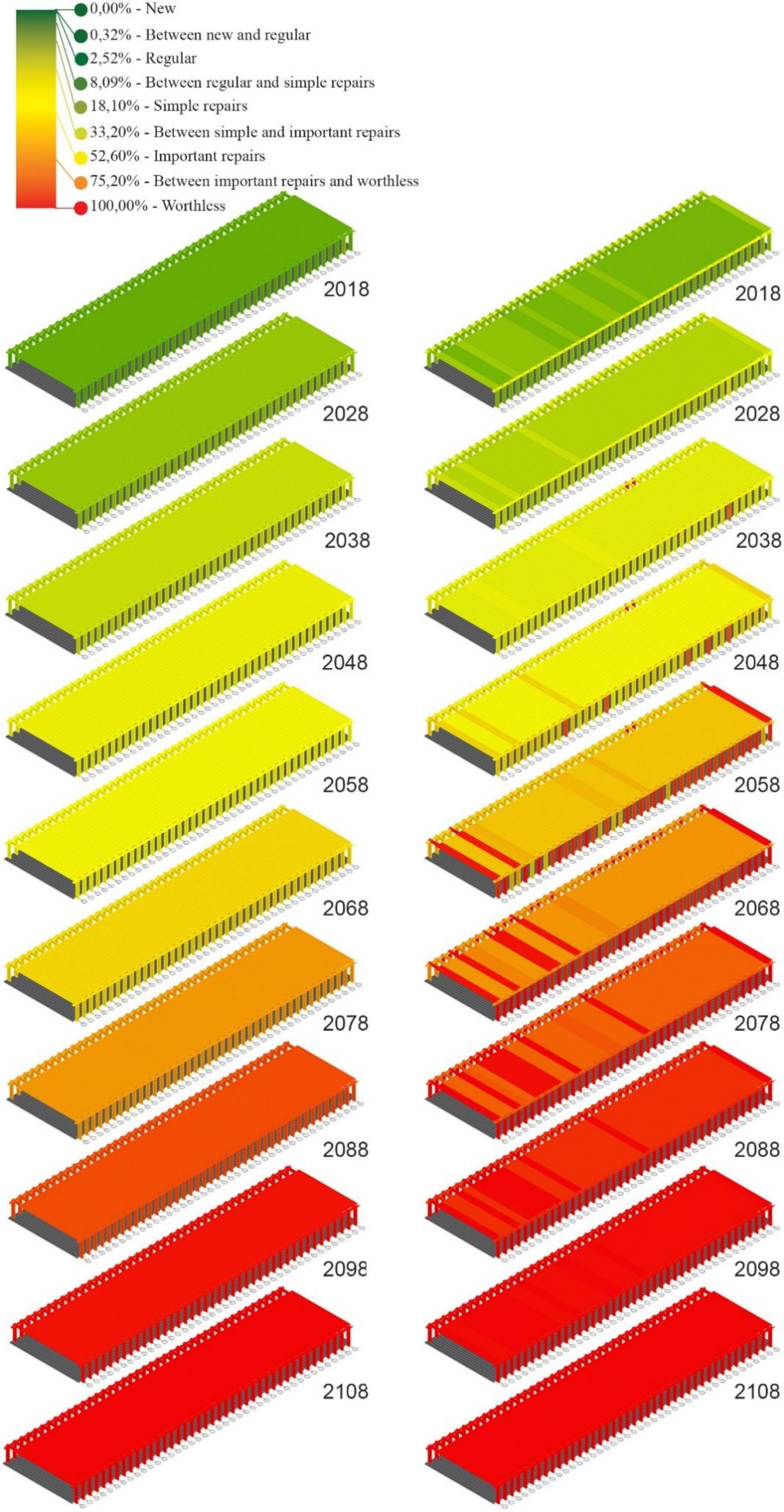
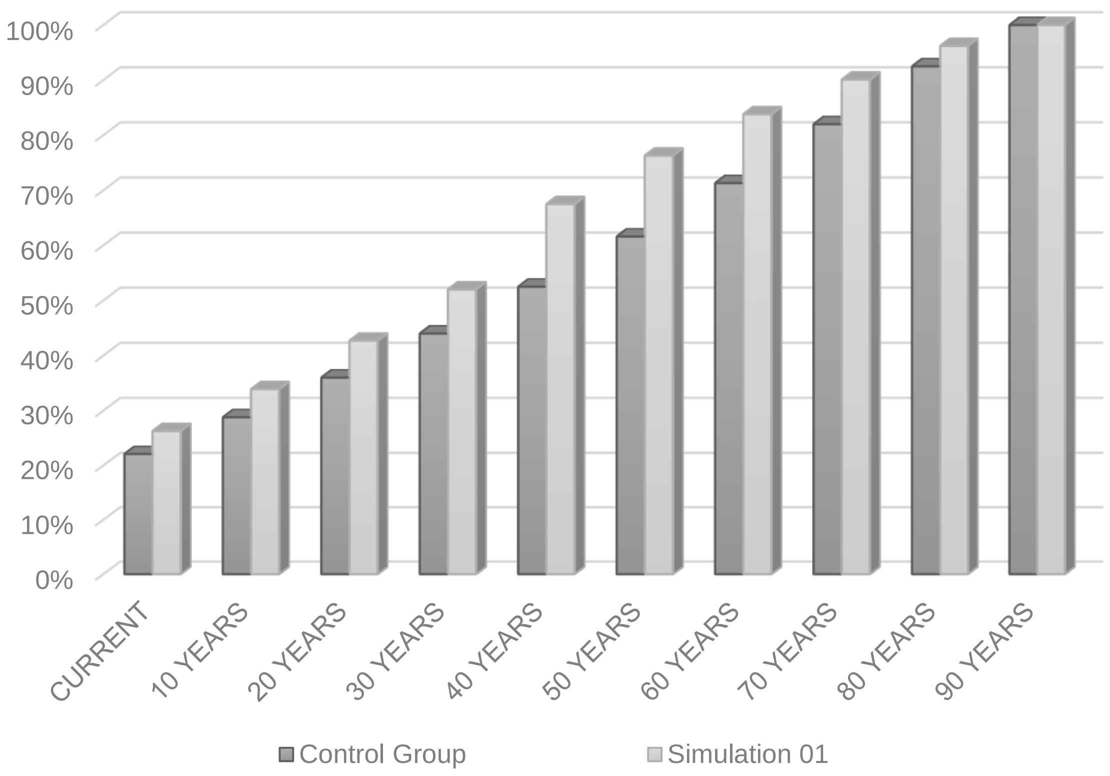


Figure 93: Control group and Simulation 01 kg comparison (private collection)

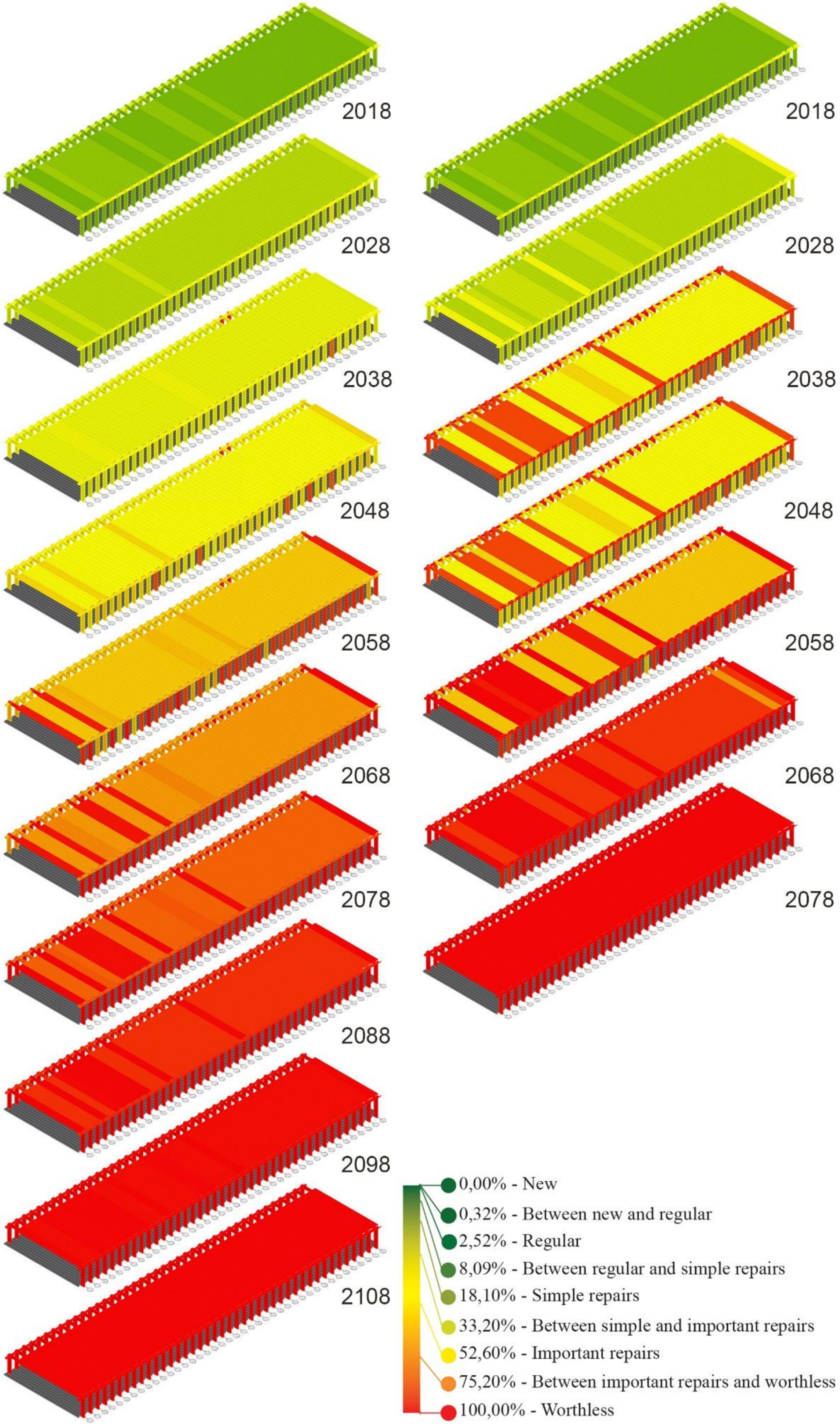


Starting with its current age of 43 years and kg of 0.26, the defect volume was doubled every 10 years, however maintaining its importance. It will increase to 0.34 in 10 years' time (2028), 0.43 in 20 years' time (2038), 0.52 in 30 years' time (2048), 0.67 by 2058, 0.76 by 2068, 0.84 by 2078, 0.90 by 2088 and 0.96 by 2098. It will also reach the end of its service life in 2105.

7.6.2.5 Simulation 02

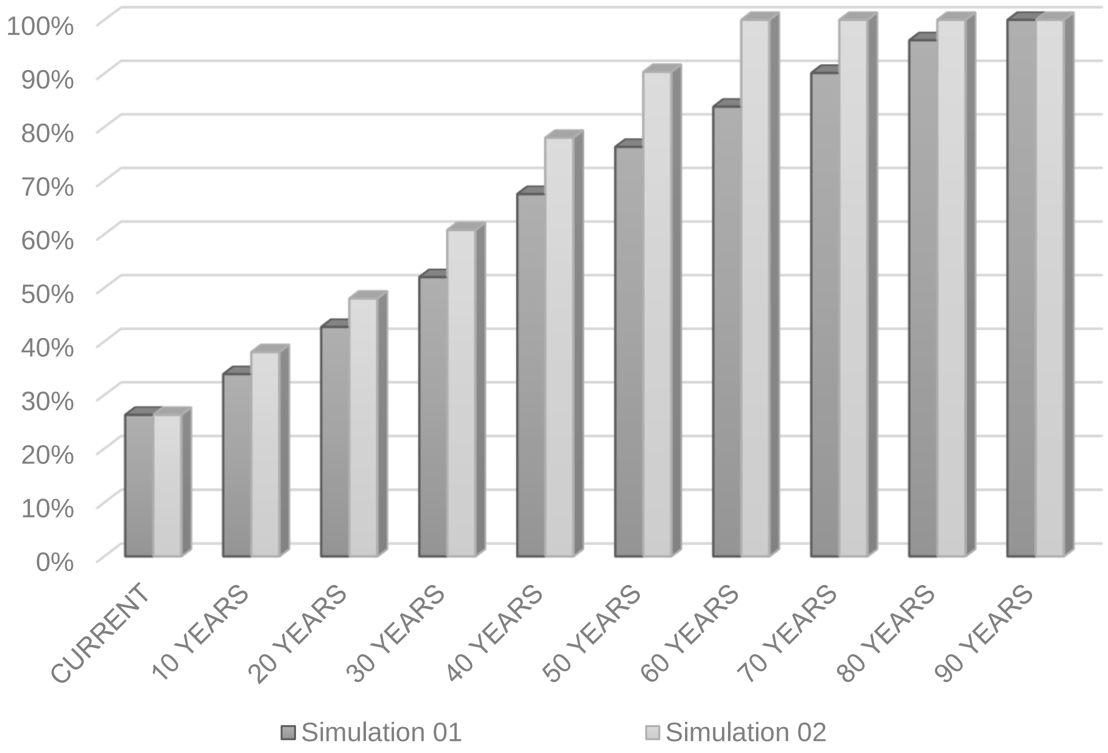
The second type of deterioration progression was considered a worst case scenario in which as soon as the deterioration progress reached 60%, it would originate a more serious defect. This simulation represents a more realistic scenario in which one defect, such as humidity or shedding, can ultimately lead to a critical defect, such as reinforcement corrosion. The comparison between the second and first simulations (Figure 94 and Figure 95) clearly demonstrates how this type of deterioration rate can seriously affect the entire building value and can even eliminate as much as 30 years of service-life.

Figure 94: Comparison between the first and second simulations. (personal collection)



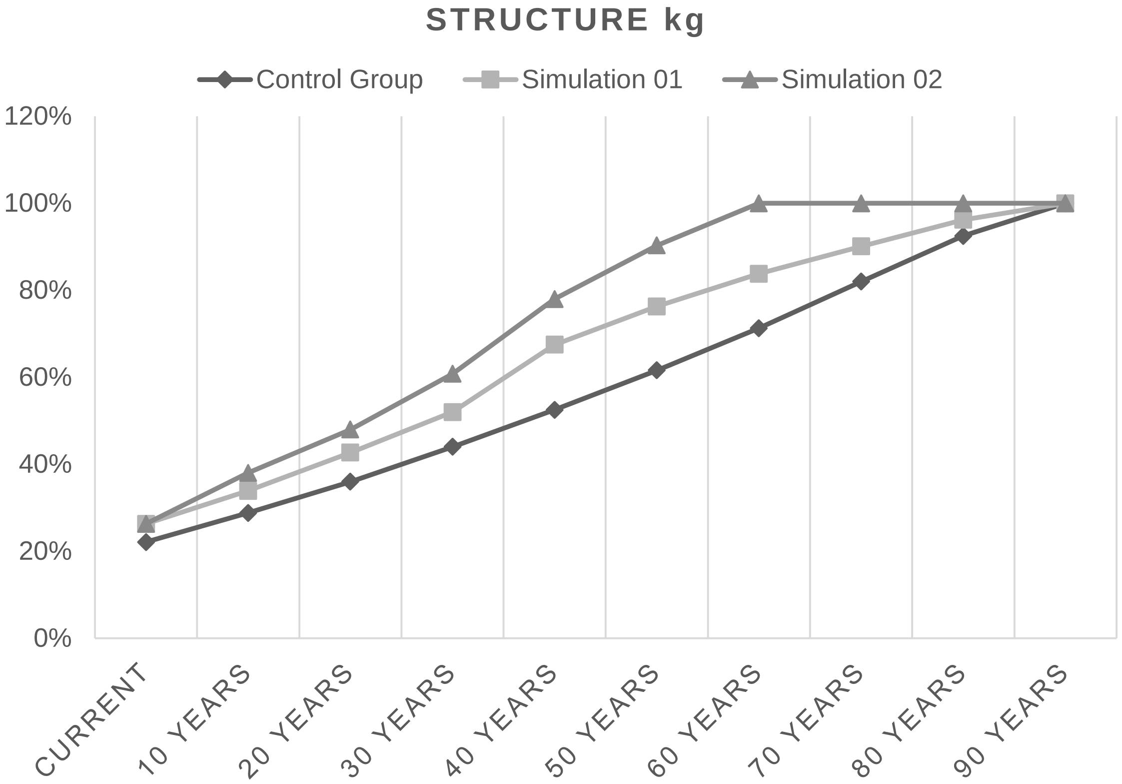
In Figure 95, it is possible to compare the depreciation rate of the first simulation and the second simulation. The second simulation represents a more realistic scenario in which one defect, such as humidity or shedding, can ultimately lead to a critical defect, such as reinforcement corrosion. Beginning at the same kg of 0.26, it will increase to 0.38 in 10 years' time (2028), 0.48 in 20 years' time (2038), 0.61 in 30 years' time (2048), 0.78 by 2058, 0.90 by 2068 and reach the end of its service life by 2078.

Figure 95: Simulation 01 and Simulation 02 kg comparison (private collection)



In Figure 96, it is possible to see the difference between the impact that diverse deterioration rates can have on depreciation over time. Although the depreciation of the control group will increase steadily and constantly, both simulations will experience a jump in depreciation value in about 40 years, at about 83 years of service-life, or about 63%. This is in keeping with the idea that the deterioration rate accelerates when it reaches 60%.

Figure 96: kg evolution through time according to different deterioration rates.



8 CONCLUSIONS

Through this research, we sought to explore the applications of VA on the AEC industry and its potential uses within HBIM for O&M in order to mitigate the threat that the lack of conservation, restoration and maintenance programmes pose to our national architectural heritage. Through VA, it's possible to accelerate rapid insight into the internal structure of data and causal relationships therein, through the use of visual representations and interactions, and to enable discoveries, explanations and facilitate decision making. The visualisation capabilities of Building Information Modelling and its ability to incorporate performance-over-time data make it the strongest tool for construction building analytics today.

With the use of a computer-aided design application software and a graphical algorithm editor, we were able to generate a parametric visualisation of deterioration degrees, condition ratings and individual and global depreciation status. After which a variety of scenarios were simulated according to different maintenance decisions and potential depreciation evolutions, which in turn generated parametric visualisation of each scenario's individual and global depreciation status through a gradient of green to red.

We were also able to visually analyse the manipulation of existing formulas, such as the Parametric GDE-UnB physical deterioration method, the Dutch Standard for defect importance and the Ross-Heidecke financial depreciation method, and propose a hybrid method which better adheres to the intended uses.

The intent here is not to accurately calculate the use case's deterioration and depreciation, but to suggest a method, supply a tool and exemplify its use.

The results were subdivided into four main stages: the inspection and mapping of element pathologies through physical inspection and photographic evidence; the scripting, comparison and analysis of different degradation and depreciation methods, from which originated a hybrid methodology; the graphic mapping, representation and visual analytics of the original methodology on the use case model and the scenario simulations for decision making.

With the hybrid method, we concluded that the use case is still at very early stages of depreciation, having lost about 27% of its value at about 33% of its service life. If all defects were corrected, however, it would have lost only 22% of its service life.

Two possible scenarios were simulated, one taking into account the geometric progression of the deterioration progress existing today and another considering that one type of deterioration progress can lead to more critical defects. Although the first maintains the projected service life, the second projected rate reduces service-life in up to 30 years. It is difficult to say which is more realistic, however the scenarios work as a parameter against which all future inspections can be compared.

Although the proposed hybrid method does solve a few issues, there are still a number of areas in which it can be improved. Suggestions for future research include: better understanding of the ESL and SSL within the Ross-Heidecke formulas; the real impact that one completely deteriorated element has on the entire structure and how much weight it should have on the depreciation calculation; more accurate visual representation of defect progression, taking into account the possibility of using textures; the use of photogrammetry and laser scanning for more accurate data acquisition of defects.

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