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Advantages of Pre-cast concrete in Airport construction

Treball realitzat per:
Kristýna Kuparowitzová

Dirigit per:
Alvar Garola Crespo

Màster en:
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Key words

Pre-cast, Cast-in-place, Concrete, Infrastructure, Air transport, Mobility, airport

Klíčová slova

Prefabrikace, betonáž na staveništi, beton, infrastructura, letištní doprava, mobilita, letiště

Abstract

This diploma thesis is an economical assessment of the advantages of prefabrication in infrastructural development with a focus on airport construction and its necessity for the project's short duration. The technology of precast panels is explained in the first part of the thesis including the specifics of different areas (structures) of the airports and their various needs. A comparison between precast and cast-in-place methods is performed regarding the construction time and financial aspects. Case study of the planned expansion and a hypothetical reconstruction at the Barcelona El Prat airport is analyzed and consequent conclusions and recommendations are made.

Abstrakt

Tato diplomová práce je ekonomickým zhodnocením výhod prefabrikace v rozvoji infrastruktury se zaměřením na výstavbu letišť a její nezbytnost pro krátké trvání projektu. Technologie prefabrikovaných panelů je vysvětlena v první části práce včetně specifik různých oblastí (objektů) letiště a jejich různých potřeb. Porovnání mezi prefabrikací a metodami betonáže na staveništi se provádí s ohledem na dobu výstavby a finanční aspekty. Je analyzována případová studie plánované expanze a hypotetické rekonstrukce na letišti Barcelona El Prat a jsou učiněny následné závěry a doporučení.

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Advantages of Pre-cast Concrete in Infrastructure Construction

1. Introduction

Airports all over the world are nowadays increasing capacities due to the growing number of its customers. This thesis considers airports as a complex of structures with different needs in terms of maintenance and rehabilitation of their aging surfaces. Airports answer to the human need of mobility and world discovering. At the same time the frequent usage of its structures is raising the necessity of maintenance and systematic reconstruction. Prefabrication is a favorable way to answer these needs. The goals of this thesis are, to state the currently used methods and to determine and evaluate the advantages of prefabrication in comparison with other construction methods. Focus is set on airport runways but the other structures as taxiways, aprons and airport facility buildings will be also brought into consideration. The outcomes of this thesis are mainly as following - a practical cost analysis performed on the case study of Barcelona El Prat airport, from this resulting conclusions regarding the analysis and recommendations in sense of the advantages. Also aims to bring into awareness the topic of sustainability in terms of reconstruction in comparison to new construction to initiate a possible discussion over its problematics.

2. Work objectives

Focus of this thesis will be on a comparison of main features of cast-in-place method and pre-cast method. The thesis is divided into two main parts. The first part is about explaining the specifics for airport constructions and the definitions of several currently used methods to fabricate a pavement surface.

These methods will be examined and explained in relation to the specific types of surface where they can be used. They will be also compared in terms of the different load replacement along the surface, the relation to the non-concrete pavements, the difference in the result quality, in terms of time of installation and most of all determining the advantages of each method. From these comparisons, conclusions will be made on how to choose a pavement method according to the characteristics of the airport surfaces.

In the second part of the thesis, the example of Barcelona El Prat airport, will be used as a case study in order to illustrate these methods and evaluate the advantages. The approach of the comparison of the individual technologies` advantages will be carried forward to determine an economical analysis to demonstrate if the proposed solutions are favorable to be used instead of so far used methods of construction of infrastructure pavements. Proposed hypothesis will be evaluated and analyzed. The results will aim to support the proving of the pre-cast method advantages.

3. State of art : Pavement systems used in airport infrastructure

There are many methods to construct a pavement in airport infrastructure also as in infrastructures in general. But maybe the vast variety of options is making the choosing of the best method so difficult. So far the main aspect of decision has been the choice of the cheapest and fastest method at the same time. This and also the lack of varieties made historically the choice easier. The tendencies are changing nowadays, because we now have many options to choose from and also because investing in long-term solutions with known revenues is favorable in terms of maintenance, profitability and sustainability. The following part of the thesis uses the SWOT analysis to help determine the strong and weak sides of the different types of pavements.

3.1 Types of pavements in general

We distinguish three types of pavement construction. The first are flexible pavements, for which the most used materials are bituminous materials such as asphalt. (Mathew, 2009) The second are rigid pavements, for which the most used material is concrete. (Mathew, 2009) And the third are composite pavements, which are usually a combination of a concrete base with an asphalt top layer. (Mathew, 2009) Sometimes the composite pavements are still considered as rigid, depending on the layers and the infrastructure classification. The pavement types vary with the amount of layers resulting different load distribution. The resulting quality also depends on the method used to fabricate the given type.

In general we could state that the choice of a specific pavement type is decided according to the availability of the used material and the knowledge and experience of its use in order to be able to construct it with available labour. (EAPA, 2003) (U.S. DTFAA, 2016) On the other hand the cost and time is still the most important factor of decision. To generalize the airport infrastructure we can state that the use of flexible pavements prevails in the construction of smaller airport runways, taxiways and apron or in smaller airports in terms of total constructed space. The flexible pavement can prove nearly the same technical properties as a rigid pavement if designed and constructed properly. (EAPA, 2003) (Delatte, 2008) On the other hand rigid pavements are more common to be found at airports with higher frequency of air traffic where low future maintenance is preferable due to high wear of the surfaces. (Tayabji, 2014)

3.2 Pavement types in comparison - SWOT analysis

The pavement types for infrastructure construction are compared in the following SWOT analysis to show in a simplified way that the flexible pavements are not the currently favorable method for the airport infrastructure. They are compared initially with the cast-in-place method of rigid pavements because, this is the currently more common method of construction.

3.2.1 Flexible pavements

Flexible pavements are a type of pavement construction, where the wheel load is redistributed by grain-to-grain contact. This type of pavement has less flexural strength. Flexible pavement consists of multiple layers Fig.1 - seal coat, surface course, binder course, base course, sub-base course, compacted sub-grade on top of natural sub-grade. Further described properties using SWOT analysis apply to bituminous - asphalt material. This pavement method is widely used in road and highway infrastructure due to knowledge of performance and low initial costs. (Mathew, 2009) (MAPA, 2014)

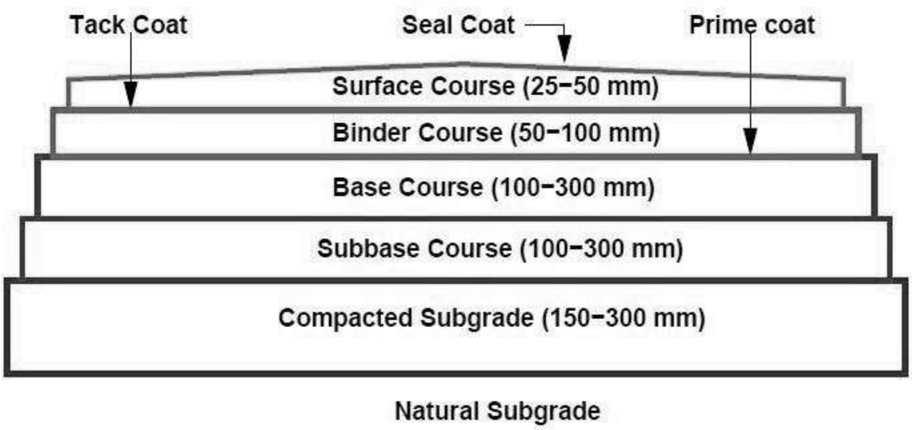

Fig. 1 : Typical cross section of a flexible pavement (Mathew, 2009)

Asphalt pavements (MAPA, 2014)

Strengths (internal, positive factors)

- Asphalt pavements are less expensive than concrete pavements in the construction phase
- Compared to cast-in-place concrete methods, asphalt dries faster
- Repairs of asphalt pavement can be situated just for the localization of damage (for concrete pavements the whole slab has to be replaced), or relayered

Weaknesses (internal, negative factors)

- The estimate life time duration of an asphalt pavement is 10 years before it has to be repaired
- Asphalt pavements tend to damage under bad weather conditions or oil leakage of vehicles and they have to be repaired frequently

Opportunities (external, positive factors)

- If maintained properly throughout the life time duration, they can last up to 20 years, which is usually not the case because the amount of new needed roads is increasing and the maintenance of old roads is solved just by sealing appearing cracks
- Flexible asphalt pavements have been used the most in the past, resulting that up to this day the most of the worlds roads are constructed with this pavement type
- The use of flexible pavements is not assumed to be completely replaced by rigid pavements, because for the necessity of large amounts of roads all over the world the cost effectiveness will still present a significant decisive factor

Threats (external, negative factors)

- Today the ambition is to replace flexible pavements by rigid pavements, especially at the most loaded roads, highway and airports
- In the question of sustainability, asphalt is produced from imported petroleum which is a non-renewable source and therefore its reserves are becoming reduced drastically
- Asphalt is reusable by melting but this process produces big amount of green house gases

3.2.2 Rigid pavements

Rigid pavements are a type of pavement construction where wheel load is redistributed to sub-grade soil by flexural strength of the pavement, by the slab interaction. This type of pavement has better flexural strength to redistribute the wheel load stress on to the pavement surface. Rigid pavements are placed directly on the prepared sub-grade or on a single layer of granular or stabilized material. Fig.2 Further described properties using SWOT analysis apply to Portland Cement Concrete material - PCC. We recognize two methods of construction : Cast-in-place and Pre-cast methods. Example of an airfield pavement in section is shown in Fig.3. (Mathew, 2009) (RPDM, 2019)

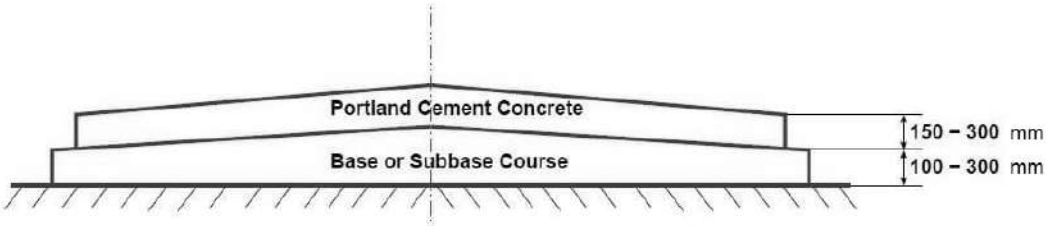

Fig. 2 : Typical Cross section of rigid pavement (Mathew, 2009)

Cast-in-place method

The continuous concrete slab constructed on site by pouring and curing concrete on site. The pavement is after sawed into segments serving as dilatation and forming separate slabs to avoid cracking of material due to water expansion in winter or the curing and drying process at construction phase. This method's types will be explained further in this thesis. (PPCI, 2017)

Precast method

The concrete panels are prefabricated with curing off site. The panels work as separate slabs that are jointed for required technical proprieties, according to the used system. We recognize numerous types of systems of panel prefabrication and panel jointures. This method's types will be explained further in this thesis. (Tayabji, 2013) (Tayabji, 2017)

Concrete pavements (Delatte, 2008) (Tayabji, 2014)

Strengths (internal, positive factors)

- The estimate life time duration of a concrete pavement is up to 40 years before it has to be repaired, there is nearly no maintenance required throughout the life time duration
- Concrete pavements don't tend to damage under bad weather conditions or oil leakage of vehicles

- In the question of sustainability concrete is produced from limestone which is a abundantly available
- Concrete pavements can be reused by crushing and used as a sub-base material for further construction
- In airport construction for the heaviness of aircraft, with the current knowledge of prestressed concrete pavements it is desirable to use only rigid pavements
- Technologically easier to be performed due to amounts of layers compared to asphalt pavements
- The durability of concrete pavements presents a long-term return

Weaknesses (internal, negative factors)

- Concrete pavements are more expensive to construct than asphalt pavements according to current cost estimates
- For concrete pavements the whole slab has to be replaced in case of damage, but this could be seen as an advantage, because the resulted pavement is more similar to the smoothness of the pavement as a whole without the presence of level inequalities
- The surface can get slippery with the presence of rain or snow

Opportunities (external, positive factors)

- As mentioned today the ambition is to replace flexible pavements with rigid pavements, especially at the most loaded roads, highway, airports
- In terms of heavy loaded pavements and reconstruction the rigid pavements types are being nowadays more often considered because of the view of cost savings in long term period while ensuring longer life time duration

Threats (external, negative factors)

- The use of asphalt pavement has history and there is more knowledge and experience, so it is often chosen over concrete pavements
- The availability of bitumen materials in a certain country presents a factor of preferable use of asphalt pavement

In conclusion of the SWOT analysis it is favorable to use the concrete pavements due to its mechanical properties, sustainability and savings on maintenance costs. The following part of the thesis will analyze the comparison of the methods of fabrication of the concrete pavements. These methods are cast-in-place and pre-cast. The Fig.4. supports the type of rigid pavements for the airfield purpose, because the load is redistributed into a wider area and therefore if the load is as high as the aircrafts are, it will present with longer durability over time. (Mathew, 2009, b) (NRMCA, 2000)

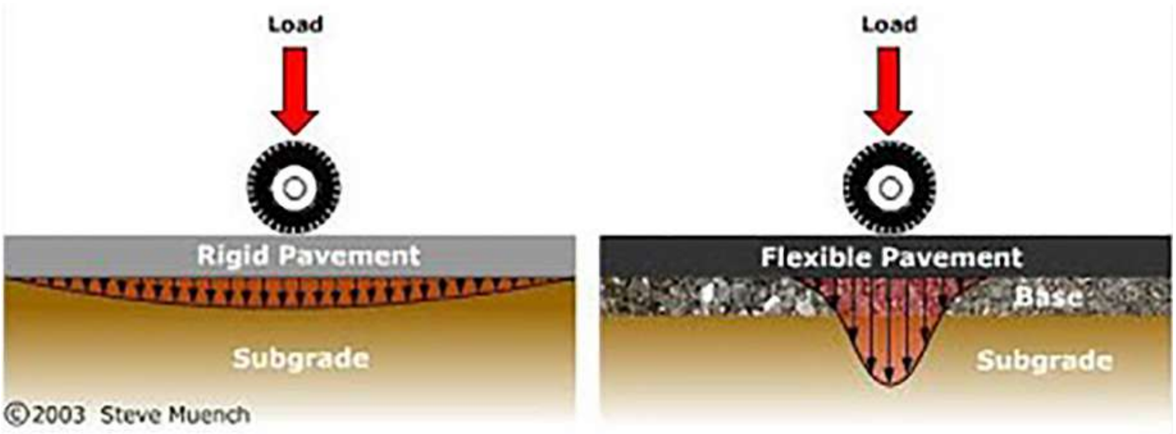

Figure 3: Rigid and flexible pavement load distribution [GooglePhotos]

3.2.3 Composite pavements

This type of pavement is a combination of a rigid pavement base with a thin layer of flexible pavement on top. The composite pavements are not a part of the SWOT analysis because in the classification of airport we distinguish either flexible or rigid pavement type. Therefore for the purpose of this thesis we will be talking about rigid pavement with an additional surfacing of a flexible pavement top layer. For the cost analysis there will be an additional cost established separately for the asphalt surfacing as an additional cost. This is because we want to compare the methods of constructing the base concrete structure. Also because some surfaces of the airport that will be analyzed do not consist of the additional asphalt layer.

3.3 Specification of airport surfaces

The word airport, if considered as a whole understands a complex of structures which can be constructed using different methods. The airports are divided into the Landside and the Airside. The Landside understands the terminal areas, parking areas for vehicles, cargo facilities and the gate areas which are the connection to the Airside. The Airside consists of runways, taxiways, stands (also called ramps or aprons) for parking aircraft and partially the gates as mentioned. The thesis focuses on the construction of the Airside. (Trapote-Barreira, 2019) (Trapote-Barreira, 2019, b)

Runway (Trapote-Barreira, 2019) (Horonjeff, 2010)

The runway is usually a rectangular surface prepared for the landing and takeoff of aircraft. This surface can have dimensions from 245 m x 8 m (considered small), 5.500 m x 80 m (considered large) up to 11.917 m x 274 m (considered huge). The runway is the surface that has to overcome the biggest sudden load as it has to stand the load of the whole aircraft at a certain speed. There is usually a minimum of two runways at an airport which when intersecting cross under an angle of 45 degrees to provide a minimal crosswind option where wind direction is variable.

Apron (Trapote-Barreira, 2019) (Horonjeff, 2010)

The apron (or stand or ramp) is the official term for the area for parking aircraft. It varies in size according to the size of the airport and number of runways.

Taxiway (Trapote-Barreira, 2019) (Horonjeff, 2010)

The taxiway is the surface used for aircrafts movement to and from the runway to the apron. Its size also varies according to the size of the airport and number of runways. The other part of the airport consists of the buildings of the terminals and connecting surfaces for its use, such as parking areas. The buildings and car parking areas are not the main objectives of this thesis.

In case of the construction of a new runway the time is also of the essence as in every construction but is not as pricey as in a case of reconstruction. On the other hand the amount of m2 of pavement is much bigger at one time.

3.4 Pavement classification in aviation construction

In aviation construction we classify pavements using the Pavement Classification Number (PCN). It is an International Civil Aviation Organization (ICAO) standard used in combination with the aircraft classification number (ACN) to indicate the strength of a runway, taxiway or airport apron. This helps to ensure that the runways etc. are not subjected to excessive wear and tear, thus prolonging their usable life and promoting safe aircraft operations. (U.S. DTFAA, 2016) (Wikipedia, 2019) The Fig.5 shows an example of an airfield pavement in section.

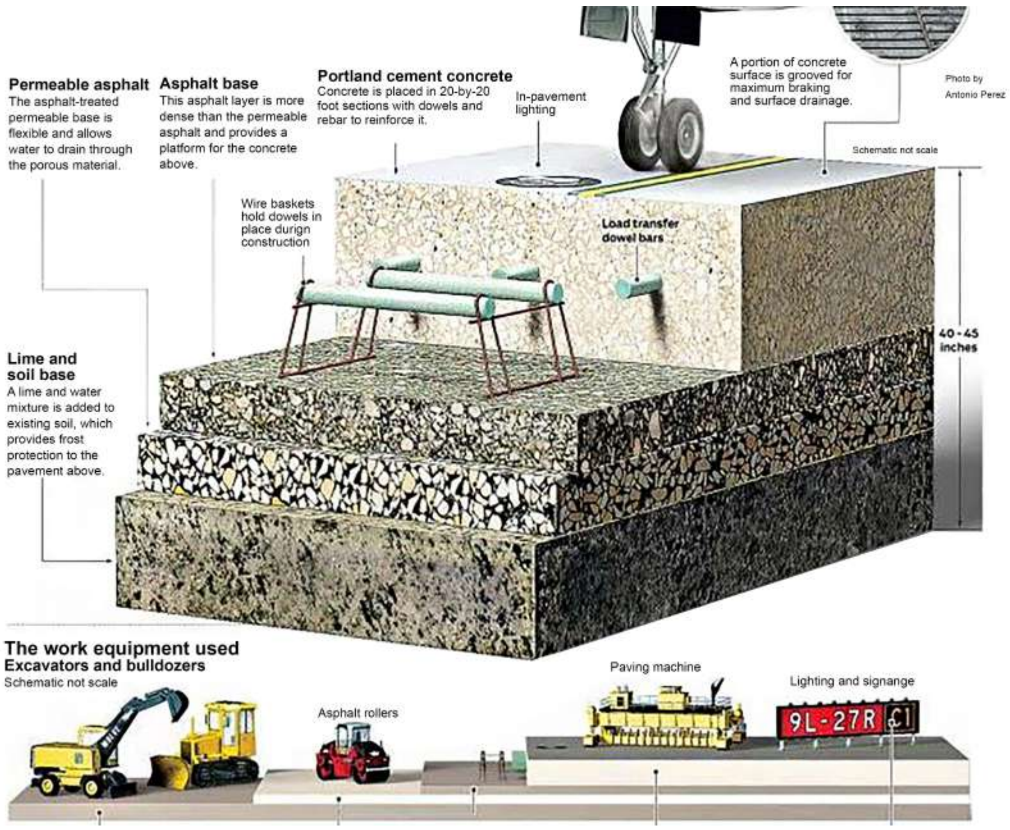

Fig. 4: Example of a concrete airfield pavement layers section [GooglePhotos]

The ACN informs us about the load that the a specific aircraft will create on the pavement. This is a key value for the design of a new airside surface, also when deciding about the marketing strategy of the airport, meaning which aircraft will the airport be able to accommodate.. For this thesis we will work with the values of already existing runways and aprons, therefore the more important is the PCN value. The PCN indicates the strength of the airside construction.

We must ensure that each of the surfaces of runways, taxiways or apron are not exposed to excessive wear and tear in order to maintain long durability and most importantly safety. In practice the PCN is a five part code with various calculated values. These values indicate the type of the pavement (rigid or flexible), the strength of the sub-grade layer of the pavement and the maximum supportable tire pressure as stated below.

Sub-grade categories (Wikipedia, 2019)

Tab. 1: Flexible pavements

Category	Strength	Value	Range of California bearing ratio (CBR) Values
High	A	CBR 15	Above 13%
Medium	B	CBR 10	Between 8% and 13%
Low Strength	C	CBR 6	Between 4% and 8%
Ultra Low	D	CBR 3	Below 4%

Tab. 2: Rigid pavements

Category	Strength	Value (*k*)	Range of *k* values
High	A	150 MN/m² (550 lb/in²)	Above 120 MN/m²
Medium	B	80 MN/m² (300 lb/in²)	Between 60 and 120 MN/m²
Low Strength	C	40 MN/m² (150 lb/in²)	Between 25 and 60 MN/m²
Ultra Low	D	20 MN/m² (75 lb/in²)	Below 25 MN/m²

Tab. 3: Tire pressure on pavements (Wikipedia, 2019)

Category	Pavement class	Maximum tire pressure
Unlimited	W	No Pressure Limit
High	X	1.75 MPa (254 psi)
Medium	Y	1.25 MPa (181 psi)
Low	Z	0.5 MPa (72 psi)

4. Methods of concrete pavement construction

4.1 Cast-in-place method

Cast-in-place method consists of pouring concrete on-site into casing forms. This includes placing the reinforcement on site and the time for the concrete to harden.
This method is currently being most widely used, due to its seemingly economical benefits, with the use of high speed hardening concrete. (ACPA, 2005)

This method is divided into:

a. JRCP - Jointed Reinforced Concrete Pavement

JRCP [Fig.5] uses contraction joints and steel reinforcement to control all the expected natural cracks. This means that the cracking occurs at joints where the reinforcement holds the the panels together.and therefore joint spacing is longer, typically 7,6m to 15,2m. There is a steel mesh reinforcement used to hold the cracks together and dowel bars are used at transverse joints to assist in load transfer. (ACPA, 2005)

Fig. 5 : JRCP - Jointed Reinforced Concrete Pavement [GooglePhotos]

b. JPCP - Jointed Plain Concrete Pavement

JPCP [Fig.6] also uses contraction joints to control all the expected natural cracks but doesn't use any reinforcement. The joint spacing is selected according to the expected position of cracks due to the temperature and moisture stresses. The spacing is usually around 6,1m. Dowel bars are used to assist in load transfer. Tie bars are typically used at longitudinal joints. (ACPA, 2005)

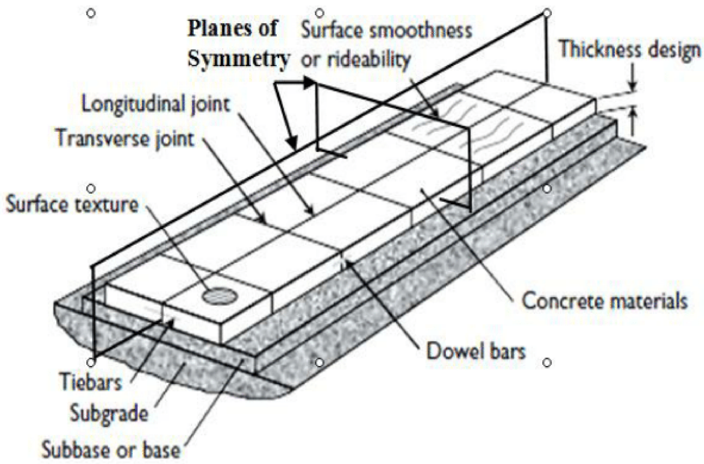

Fig. 6 : JPCP - Jointed Plain Concrete Pavement [GooglePhotos]

c. CRCP - Continuously Reinforced Concrete Pavement

CRCP do not require any transverse contraction joints. The expected cracks appear at intervals of 0,5-1,8m and the sufficient continuous reinforcement holds the concrete together tightly. The design process of this type consists of determining the optimal spacing of the cracks. This type is more expensive than JPCP and JRCP due to the amount of reinforcement but can demonstrate higher life time duration. Typical design service life is around 30 years and with that period there could be a costs return expected. (ACPA, 2005)

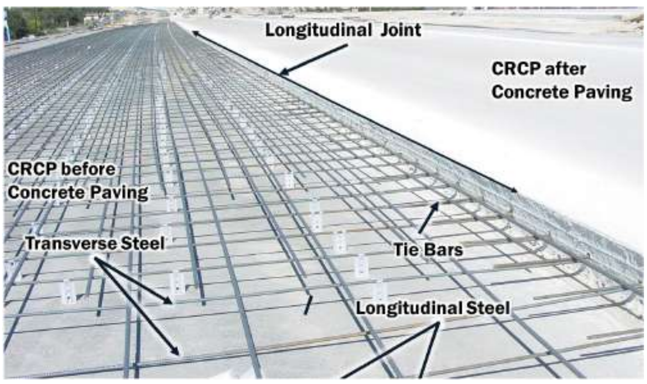

Fig. 7 : CRCP - Continuously Reinforced Concrete Pavement [GooglePhotos]

4.2 Pre-cast method

Precast concrete technology (also known as PCPS - Precast Concrete Pavement Systems) has a long history, it has been used since ancient Rome, but nowadays its use has been suppressed, by other methods like cast-in-place or asphalt for the pavement construction. It is because of the seemingly faster and more economical construction. Since ancient Rome we have upgrade the composition of the concrete mix also as the huge variety of possible reinforcement. And we have developed the ways of casting and curing. Precast method or prefabrication, consists of casting concrete into a reusable mold or `form` and curing in controlled conditions to create a panel that is ready to be placed on site. The panel includes prestressed reinforcement, to overcome concrete weakness in tension. This is especially useful in the transportation infrastructures, where the pavement is heavily loaded by the weight of vehicles. As for airport runways the load is increased by the load while landing. (Chen, 2014) (Tayabji, 2008)

Production in an indoor environment results in improving the quality of the final element panel, because the conditions influencing the panel during the hardening process can be controlled and stabilized. We can control the consistency of the concrete mix, procedures of vibration and proper curing. Precast objects reduce or eliminate curling, strength, and air-entrainment problems that are common with conventional concrete paving. Importantly, precast objects are also being both prestressed during their plant production and post-tensioned during their installation, which is not possible for the cast-in-place approach. Since the formwork material is usually steel, it can be reused multiple times and this way lower the production costs. Automation and mechanisation can substantially reduce the number of working hours. Since the curing conditions are controlled the result mechanical properties can be ensured with a smaller thickness of the panel than in case of the cast-in-place method. Also material savings are usually the case because the fabrication doesn't give in the time pressure as on site. The prestressed properties are easier to ensure then in on site construction. Also post-tensioning reduces pavement thickness and increases durability by minimizing or even eliminating cracking and ties the individual panels together. The load transfer takes place in between the panels.

All this leads to increasing the life time of the panels and therefore reduces the maintenance costs.

The question is most certainly about the cost of transport, which presents the highest ratio in the total costs of prefabrication. This factor will be more developed in the case study of this thesis. The transport costs can not be unified due to differences of dimensions of panels for each construction and according to the distance of the construction plant from the site.

The speed of construction with use of the prefabrication method should be the strongest advantage. The fact of producing simultaneously and automatically presents huge advantage of time savings. The production can also take place in any natural weather conditions since its in an indoor environment. The formwork can be also reused right after extraction of the finished panel. No extensive, elaborate on-site facilities are required.

The difference of a panel for heavily loaded pavements or standardly loaded pavements is only in the amount and placement of reinforcement.

In the end the main importance is at the stage of planning and design which needs to be precise enough, to ensure the final properties of the panel. In terms of new construction of huge dimensions, the construction plant could be placed on site to reduce the transport costs to the minimum.

Installation of panels

Adjacent panels are tied together with joints (cast-in-load) or post-tensioning systems. The systems are used for replacing an established segment of approximately 10 panels according to the used system. The designed segment should consist of a full width of the constructed pavements (width of highway, runway, etc.). In comparison to cast-in-place method, the pre-cast construction should speed up the construction two to three times. The essential for this method is the plan of the works which has to be well organized in order to achieve the time savings. Depending on the system, almost no curing is required apart from smoothening the surface so the pavement is ready to be used upon installation. This method also presents substantial safety advantages because the method is systematic and therefore easy to learn by workers also without experience with this method. (Chen, 2014) (Tayabji, 2008)

Fig. 8 : Pre-cast panels formwork (Tayabji, 2016)

Fig. 9 : Pre-cast panels fabrication (Tayabji, 2016)

This method is divided into:

A. P-PCP - Prestressed Precast Concrete Pavement (for intermittent repairs)

This method consists of using hight speed strengthening concrete for fast track immediate repairs of pavement where any long duration or delays increases the user costs.

B. J-PCP - Jointed Precast Concrete Pavement (for continuous applications)

a. Fort Miller SuperSlab system
b. Kwik Slab system
c. Uretek Stitch in time system
d. ModieSlab system
e. Other systems (System used at the New York La Guardia International Airport, Systems used in Japan for tunnel roads and airport pavements)

a. Fort Miller Super Slab System

In this system the slabs are placed on a fine bedding material maximum size of 12mm. The joints are fitted with standard dowel bars for load transfer. The voids are eliminated with use of grout and the surface is smoothened with a diamond grinding. The interaction and load transfer between the panels consists of dowel bars positioned into prepared slots in existing slab and grouted. Unlike the other systems the jointing slots are positioned at the bottom of the panels and therefore are not directly exposed to the structural and environmental loading. This fact has also major positive influence on the structural behavior of the system. The thickness can be adjusted according to the necessary load to be transferred and the use of high performance concrete. This system is the most used and has been field tested and therefore provides the most experience data up to date. (Tayabji, 2008) (Novak, 2017)

Fig. 10 : Fort Miller Super Slab System (Tayabji, 2016) **Fig. 11 :** Fort Miller Super Slab - Joint detail (Tayabji, 2016)

b. Uretek System

This system was designed for fixing faulted joints and restoring load transfer to concrete pavements. "*URETEK has developed two patented technologies. The first is the URETEK® Method which is the process that employs high density polyurethane foam to lift, realign, under seal, and void fill concrete slabs which are resting directly on base soils. The second is the Stitch-In-Time® Process which is a repair system for restoring load transfer to jointed concrete pavements that are cracked, spalled or otherwise damaged. Pavements undergoing repair are first under sealed using the URETEK Method and then the Stitch-In-Time Process is applied to restore load transfer."* (Novak, 2017) (URETEK USA, 2005)

The panels are lowered into the excavated repair site and are elevated to the requested pavement by injecting polyurethane foam under the panels. After the panels are stitched to the existing slab or another panel using fiberglass boards.

Fig. 12 : URETEK Method System [GooglePhotos] **Fig. 13 :** URETEK Stitch-In-Time System [GooglePhotos]

c. Kwik Slab System

The prefabricated panels include Kwik Joint steel couplers that rapidly interlock allowing the two-way continuity throughout the entire pavement slab. Each panel has a number of male-type and female-type components that interlock with the adjacent panels. This system is characteristic by fast and easy completion at site due to the interlocks. It maintains a continuous reinforcement in two ways with minimum grouting used. The system simulates Jointed Reinforced Concrete Pavement. There is a limit to the total length of the panels because there would be necessary to use expansion joints and they haven't been incorporated into the Kwik Slab system. (Tayabji, 2008) (Novak, 2017)

Fig. 14 : Kwik Slab System - (a) female-type and male-type components of interlocking system; (b)steel connector sockets; (c) panel installation; (d) injection of high-strength grout. (Novak, 2017)

d. Michigan system (Precast Concrete Panels for Full-Depth Repair)

This system, which was invented at the Michigan State University and serves for the intermittent pavement rehabilitation. Precast concrete panels are fitted with three or four dowel bars which ensure the load transfer between the adjacent elements. The panels are placed directly on a prepared sub-grade covered by a flowable fill as a cement-based self-leveling material. The dowel bars fit into slots cut out in an existing slab or adjacent elements. When the precast concrete panels are installed, the slots at the top of the panels and the dowel bars are grouted with a cement-based composite. (Tayabji, 2008) (Novak, 2017)

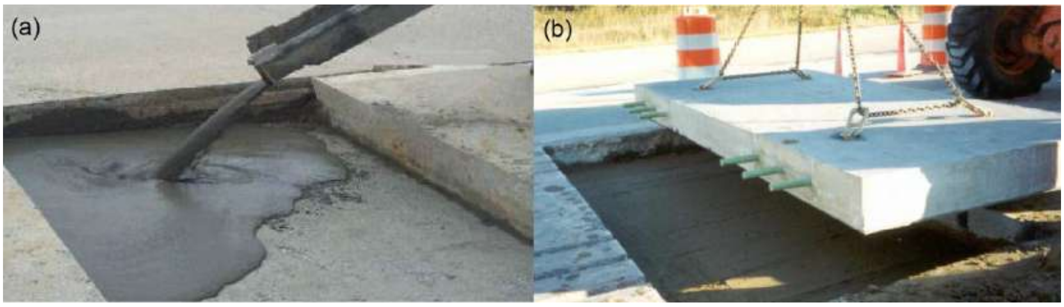

Fig. 15 : Michigan system, (a) sub-grade preparation – flowable fill; (b) panels installation. (Novak, 2017)

e. ModieSlab System

This system was developed in the Netherlands as part of the “Roads to the Future” program. It consists of a full width precast concrete slab that is placed as a bridge on the pavement sub base. The slabs are connected to underlying precast reinforced concrete crossbeams with prestressed anchors and sliding planes and no dowel bars are present. Developments are being made to place the slabs directly on an existing pavement without the need of using piles and beams. The slab behaves as a complete road structure including rainwater gutters penetrated through a layer of porous concrete on the bottom of the slab. Above that there is a layer of reinforced concrete. It also contains a pipeline system to regulate the temperature of the slabs and dilatation in presence of snow and ice. (Tayabji, 2008) (Novak, 2017)

Fig. 16 : Modie Slab System (Tayabji, 2008)

Fig. 17 : Modie Slab System (Tayabji, 2008)

4.3 Examples of Pre-cast applications in existing airports

Use of precast concrete pavement is considered to be a high pay-off alternative for rapid repair and rehabilitation of airfield pavements. Even though there are some existing applications of this method, it is still a relatively new method and therefore not trusted as much as the other fast track repair methods. More precisely it is not an explored method in the European constructions, but the available data and tests indicate that it should out-stand the other methods. (Tayabji, 2014) (Tayabji, 2010) (Reza, 2012)

1. PANY/NJ evaluating for possible rehabilitation of Taxiway A at La Guardia Airport

-incorporates a thick AC pavement that requires constant repair due to rutting caused by queuing aircraft but this option is not preferred because of past performance issues

-the cast- in place concrete pavement option is not feasible because of time constraints.

-as a result, PANY/NJ is seriously considering use of precast paving to rehabilitate sections of the taxiway over several 55-hour weekend closures.

-to develop engineering information, PANY/NJ constructed two 61m test sections at a non-critical taxiway during 2002.

-one test section used 41cm thick and 3,8m by 7.6m panels and the second test section used prestressed 31cm, 3,8m by 7,6m panels. (Tayabji, 2008)

2. St. Louis international Airport – for slab panel replacement (Tayabji, 2008)
3. Dulles International Airport – for slab panel replacement (Fort Miller and Uretek systems) (Tayabji, 2008)
4. The US military has also been evaluating use of precast pavements for expedient airfield pavement repair and rehabilitation. (Tayabji, 2008)
5. Japanese Precast Reinforced Concrete (PRC) Slabs

- Airport taxiways application of an experimental pavement at Fukuoka Airport in 2004, the joint design has been improved and fiber reinforced concrete has been tried at the surface portion of the PRC slab to prevent cracking.
- Slabs are placed on an asphalt interlayer to prevent pumping in the granular base course underneath. Gaps between the slabs and interlayer are filled with a grouting material. The standard dimension of the slab is 1.5 m in width and 5.5 m in length. The thickness varies from 20 to 25 cm. (Tayabji, 2008)

4.4 Selecting the most appropriate method for an airport

It is clear that each airport should be evaluated individually in terms for the suitable construction and reconstruction method of its surfaces. There might be also tradition based or material availability aspects that could deny the pre-cast construction methods. Anyway the purpose of this thesis is to propose an objective view on the problematic and to highlight the technical facts.

Significant aspect about airport construction is that in the case of both new construction and reconstruction you have to have in mind the marketing strategy of the airport. The marketing strategy will determine the type and frequency of aircraft usage and therefore the pavement must be adjusted to this. The strategy of the airport will also determine costs of construction and maintenance that can be afforded. The area where the airport is place will define the climate conditions for which the pavement must be designed. The length of the runways, the areas of taxiways and ramps all depend on the aircraft size that will be present at the airport.

If we suppose we have chosen the concrete pavement type, due to the results of the SWOT analysis, in terms of selecting the method of the pavement construction there are several key factors that come into consideration. These key factors are initial investment, maintenance cost with durability and time of construction.

Knowing this we can use this factors as evaluation criteria. We will use the multi-criteria analysis further-on in the thesis to determine the behavior of the cost in terms of a chosen period of time.

From the pre-fab pavement types as stated above, the most logical solution for the case study of airfield is the Fort Miller Super Slab pavement system due to its joints that are positioned under the panel and therefore the resulting pavement has a required smoothen surface. Also because there is more available data on the slab performance. They have been tested with a Heavy Vehicle Simulator and existing project have been monitored and evaluated. (Tayabji, 2010) (Kohler, 2014)

5. Evaluation methods of Pre-cast and Cast-in place (Methodological approach)

5.1 Methods based on cost, Financial analysis (Daniel, 2002)

The applied method to evaluate the stated hypotheses on the case study is a multi-criteria analysis. As the name hints it is a method based on multiple criteria that help us compare the values of each criteria. The factors of the multi-criteria analysis can be both qualitative or quantitative. The advantage of this method is that the analysis isn't based only on the factor of cost. It's because the cost is not a sufficient factor to be considered in the construction industry. Saying that the initial investment for the project is lower does not mean that this solution will be favorable in terms of time, duration or quality.

Especially in infrastructure projects the time is of the essence and the speed of construction can play a critical decisive role. Other factors like maintenance costs and design lifetime are also essential factors to consider.

5.2 Costs that will be consider for the analysis

For the purpose of this thesis the costs that will be considered are based on the available and accessible information. For the Pre-cast method the costs are based on estimates generated by the Super-Slab® company (Att.3.). These costs have been found to be comparable to the costs of the Spanish Cost Database and therefore the selected value is the average from the proposed range. For the comparison of the cast-in-place methods and the flexible pavement, the costs come from the mentioned Spanish Cost Database (Att.6.).

The costs from both these sources consider many items and result in a value. These costs will be described in terms of which items they contain, but it not specified these costs contain the labour, the material and the transportation to site. The maintenance costs will be represented separately. The costs of installation pre-cast panels and casting concrete with the cast-in-place method depend on whether they are constructed continuously or intermittently. Continuous construction is without break, cessation, or interruption; without intervening time. Intermittent is stopping and starting at intervals; coming after a particular time span; not steady or constant. This is an important criteria which will be specified for each hypothesis because it directly influences the price of each method.

5.3 The impact of time in the analysis

The time is an important criteria in the analysis. There will be a determined period of time for which the analysis will be made. This is the predicted period of duration of the pre-cast method and for the cast-in-place method. Another time period has to be determined for the duration of the realization of construction or reconstruction of each hypothesis. Possible closures of a certain part of the airport will be considered in terms of the duration of the closure and it will be evaluated, what is the impact on the airports operation. On the other hand, the actual time of construction of the hypothesis will be compared for the two methods, since there is a big technological difference in realization and this directly influences the time needed for closures.

5.4 How a viability plan is made / Feasibility study

The viability plan, in this case a plan specifying all the aspects necessary for starting the project of each hypothesis and determining if they are viable. Considering the planning permissions, in the purpose of the analysis we suppose the construction has been granted. In reality the reconstructions should not pose a problem as the intervention has already been made, therefore a maintenance in terms of reconstruction of the insufficient parts is supposably favorable. In terms of the new construction, this is based on obtained information that the plan of extension is in negotiations so if there is an issue with the additional surfaces to enable the construction, this is not a subject to the analysis, because the hypothetical scenario can only be realized if granted by a permit. The similar applies to any other legal approvals because the analysis does not directly depend on them. The realization can not take place without them.

In the question of the sub-grade, which is unique for this case study, the necessary stabilization of the wetland grounds will not be considered, because is would be necessary to perform for both methods of pre-cast and cast-in-place. This aspect, with the aspect of construction permits is in close connection with the subject of environmental impact. In terms of if it is ethical to perform this type of construction in relation to the protected landscape area, it will not be considered. The aspect of environmental impact, in terms of sustainability will be presented in two aspects. One is the choice of reconstruction instead of new construction, which in terms of constructed and therefore devaluated landscape should present an obvious advantage. The other is the fact of supporting a method of pre-cast constructing which presents demonstrably lower CO2 emissions.

In terms of a potential budget of expected cost, there is no such budget determined. The costs are assembled according to databases, existing projects and available data on new technological methods. As for the maintenance costs, they are considered as both an economical value but also as a long term performance benefit.

5.5 Multi-criteria method, Based on economic and non-economic concepts (EC Regional Policy, 1997) (DCLG, 2009)

The multi-criteria analysis is based on both economic and non-economic aspects. As stated below the economic concepts will be represented by defining the different costs and evaluating the value of time in terms of loss of operations due to necessary closures. In this thesis as we will found out, the cost will turn out to be the most important criteria, and evaluable according to the available information. For the purpose of this thesis the hypotheses will be evaluated with the cost-effectiveness analysis. The multi-criteria analysis if further developed would be a possible way to include other decisive criteria for e.g. the sustainability and environmental aspects.

5.6 Basis of the analysis

The basis of the analysis is the case study of Barcelona El Prat airport and the fact that the number of passengers is increasing every year. Therefore the demand is estimated to reach the capacity of the airport. Since the strategy of the airport is to satisfy this demand, measures need to me made to increase the capacity. The extension of a runway is something the Barcelona El Prat airport is already discussing and considering. The idea for the two other hypotheses comes from a general assumption of the European airport and their aging and detrition.

5.7 Valuation methods (Saarikoski, 2016) (Akhtar, 2009)

The valuation methods are oriented to reach the goals of this thesis. The evaluation will be made to compare which are the advantages of the pre-cast method contrary to the cast-in-place pavement construction method. Since in Europe the construction and reconstruction of the airports is a responsibility of the airport and the government, the analysis is made from the point of view of the airport. Meaning that the analysis tries to reach minimal possible cost for maximal advantageous properties. It is supposed that the costs of the air fare for the passengers do not depend on the construction and reconstruction costs. The supposed process of the constructions and reconstructions is proposed in the maximum beneficial way for the operations of the airport. The goal is to interrupt the airport traffic as least as possible.

6. Case study of Barcelona airport

6.1 Introduction

The idea of the case study is to present scenarios in which the pre-cast pavement would be used and evaluate its advantages. The case study is structured into three hypothetical scenarios, that are based on different approaches of airports needs. Based on the airport situation in Europe in general, on the observations of Barcelona El Prat airport and on the fact that the Barcelona El Prat airport is planning a runway extension. The pre-cast method is considered as a long term solution and therefore with an economical return in terms of time. For the pre-cast pavement, the Fort Miller method, previously explained, will be used to illustrate and evaluate the hypothetical scenarios. The construction method was selected for these hypotheses not only because of its benefits but also because of available data. The fact that the selected panel type has been previously tested and performed provides data to evaluate the method in comparison with the cast-in-place.

6.2 Airport characteristics

History and current state

The Barcelona El Prat airport dates back to 1916 but the majority of the constructions were completed around 1948. The main runway from this year is currently being used as the primary runway together with a third runway from 2009. The third runway was open, also as the building of the currently new terminal, as an answer to heavy growth to provide better service to more passengers. (AENA, 2016) (barcelona-airport.com, 2019)

The airport is divided into the older zone with the old terminal (today called Terminal 2 or T2) which was the main building until 2009. (Fig. 18) It was designed and constructed just before the Olympic Games in Barcelona in 1992. Today it operates only 30% of the flights mostly by low cost and regional carriers.

The newer terminal (today called Terminal 1 or T1) now operates 70% of the flights. With the new terminal the airport is able to handle up to 55 million passengers per year and reach 90 operations per hour. Currently handles around 47 million passengers per year. (AENA, 2016) (barcelona-airport.com, 2019)

Fig. 18: Current status of the Barcelona El Prat airport (Trapote-Barreira, 2019)

The current predictions indicate that the World long term demand will increase exponentially (Fig. 19). As for the situation for Barcelona El Prat airport the demand should increase up to 50 million passengers in 2020 (Fig. 20). The intention for the near future is the expansion of the short runway in order to be able to function fully as the main runway, to accommodate all low cost and large aircraft.

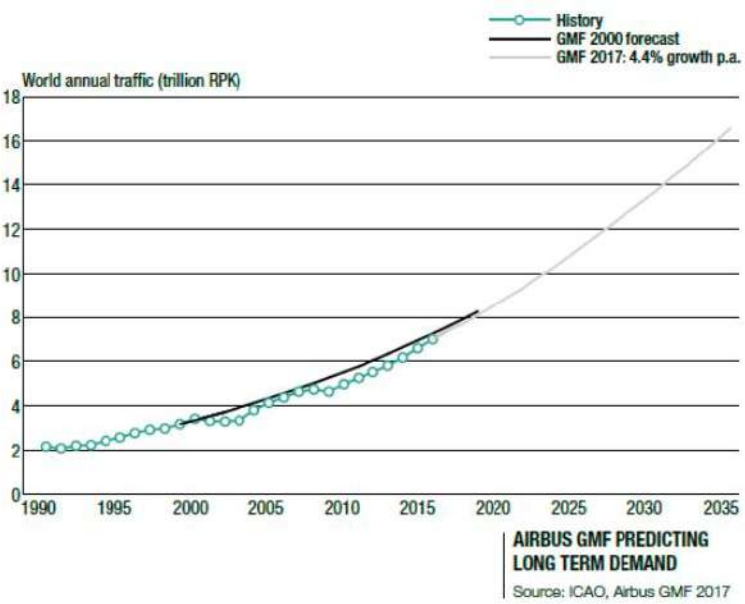

Fig. 19: Prediction of the World long term demand by Airbus (Trapote-Barreira, 2019)

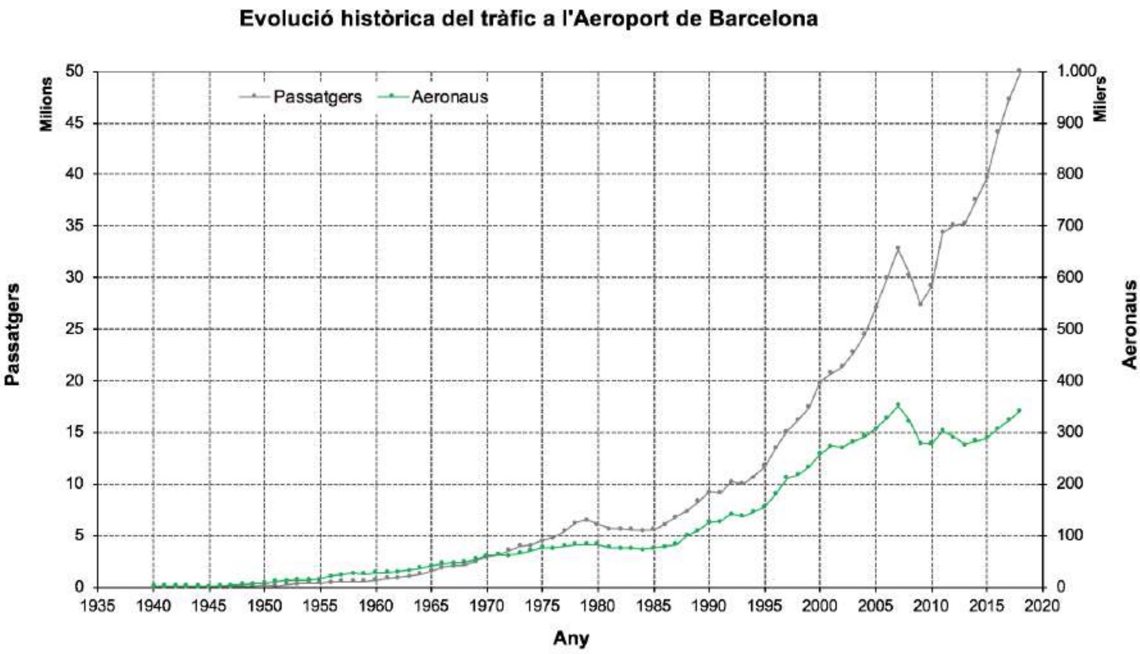

Fig. 20: Evolution of traffic at Barcelona El Prat airport (Trapote-Barreira, 2019)

<u>Placement</u>

The Barcelona El Prat airport is situated close to the sea located in the south-west from the city of Barcelona. (Fig. 21) The location of the airport has its strong advantages and disadvantages. The reason of the placement was historically as simple as there was no other area with sufficient land for the airport needs, back in the day. In terms of accessibility from the city center it is very convenient for passengers because it is fast to arrive to and from. On the other hand the previous expansions are predicted not to be sufficient in the future and therefore there is not much space left. Also since the location is near to the sea, the grounds are mostly wetlands which are not suitable for airside construction.

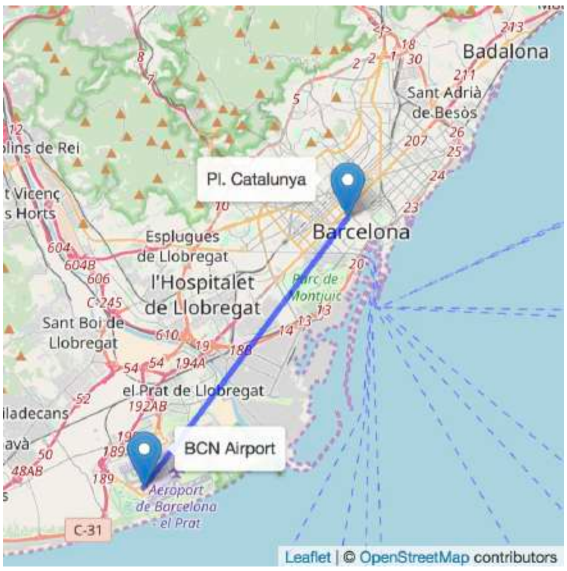

Fig. 21: Location of the Barcelona El Prat airport [Google Maps]

Airport classification

The Barcelona El Prat airport has an Aerodrome Reference Code of 4E airport according to ICAO (International Civil Aviation Organization). The number of the classification stands for the aircraft size that the airport can operate, in this case 4 - the aircraft reference length can be above 1800m (typical aircraft Boeing 737/700 or Airbus A320). The letter stands for the maximum aircraft wingspan, in this case E - 52 m but < 65 m. (Wikipedia, 2019)

Airport Airside and Land side

To clarify the used airport terminology, as already mentioned the airport is divided into the Airside and Landside. The Airside consist of all activity related to the aircraft operations, therefore the runways, taxiways and ramps. The Landside understands the general activity and services for passengers, therefore the terminal buildings, luggage facilities, parking, cargo and business facilities. (Trapote-Barreira, 2019)

Airside Pavements classification

As explained in part 3.4 of this thesis, there are standards to classify the pavements of an airport construction. For the Barcelona El Prat airport the classification is as follows:

RWY	DIRECCIÓN // DIRECTION	THR	RESISTENCIA // STRENGTH
02	019°	41°17'15.93''N 002°05'05.41''E	RWY 02/20: PCN 91/F/A/W/T RWY 07L/25R: PCN 88/F/A/W/T RWY 07R/25L: PCN 126/F/A/W/T TWY: PCN 61/F/A/W/T EXC: B6 a // to B10: PCN 59/F/A/W/T; D4, R1 a // to R6: PCN 55/F/A/W/T; ES1, FS1, GS1, HS1, LS1, MS1: PCN 141/R/A/W/T; G1 a // to G3, G10 a // to G12, K1, K11, M16, N16, S11 a // to S13, Y5 a // to Y7, Z5 a // to Z7: PCN 70/R/B/W/T; U4 a // to U6: PCN 120/F/A/W/T. APN: RAMPA-0 // RAMP-0: PCN 50/R/B/W/T; RAMPAS-1 & 2 // RAMPS-1 & 2: PCN 79/R/B/W/T; RAMPAS-3 & 9 // RAMPS-3 & 9: PCN 87/R/B/W/T; RAMPAS-10 a 17 // RAMPS-10 to 17: PCN 141/R/A/W/T; RAMPA-30 // RAMP-30: PCN 118/F/A/W/T; RAMPA-31 // RAMP-31: PCN 148/R/A/W/T; RAMPA-32 // RAMP-32: PCN 149/R/A/W/T.
20 **(1)**	199°	41°18'33.46''N 002°05'40.78''E	
07L	065°	41°17'41.44''N 002°04'19.02''E	
25R	245°	41°18'20.61''N 002°06'13.43''E	
07R	065°	41°16'56.32''N 002°04'27.66''E	
25L	245°	41°17'31.99''N 002°06'11.81''E	

Fig. 22 - Barcelona El Prat airport pavements classification (Attachment 1.)

Legend :
RWY - Runway
TWY - Taxiway
APN - Apron, RAMPA - Ramp (Apron is the official terminology, Ramp is most commonly used)
PCN - Pavement Classification Number
F - Flexible
R - Rigid
A - High sub-grade category
B - Medium sub-grade category
W - Unlimited tire pressure category
T - Calculated through technical evaluation
91,88,126,59,55,141,70,120,50,79,87,141,118,148,149 - Values of load carrying capacity

6.3 Introducing three different hypotheses

The three hypotheses are focused on different parts of the airside of the airport. They are marked in the plan of the Barcelona El Prat airport below. (Fig.23) All of them come as a result of the increasing number of passengers per year and therefore the necessity of increasing the airport capacity. The approach is to prefer reconstruction of the existing structures instead of increasing the constructed area. This for two reasons, one is that there is not enough new land available and the second is to try to be most effective and sustainable. (Att.1.)

The first hypothesis is a reconstruction of an existing ramp at the older Terminal T2. It is currently in a sorrowful condition and should be functional and representative. The second hypothesis works with the idea of the need of replacing the runway continuously according to the damaged areas. The airport has three runways and its heavy use is causing damage that in case of need have to be repaired immediately with the least traffic interruption. On the other hand the third hypothesis is based on a plan of extending the runway 07R/25L. This runways is suitable only for the landing or take-off of light low-cost aircraft but the airport strategy for the future presents the need of this runway to accommodate all types of aircraft.

The chosen method is a PCPS method (Att.2) - with specific data for the analysis from Fort Miller Super-Slab® (Att.3,4) pre-cast panel, which has been developed in the United States of America and is now becoming more and more popular due to its advantageous technical properties and proven experience from tests and installations. Also due to the necessity of fast track repairs, where the highways need to be rehabilitated in short period night time closures, not to interrupt the heavy traffic. In the United States of America, this method has been used mainly in the highway pavement rehabilitation, but the panel has been previously tested also in terms of functionality at the airfield. (Attachments 2.,3.,4.)

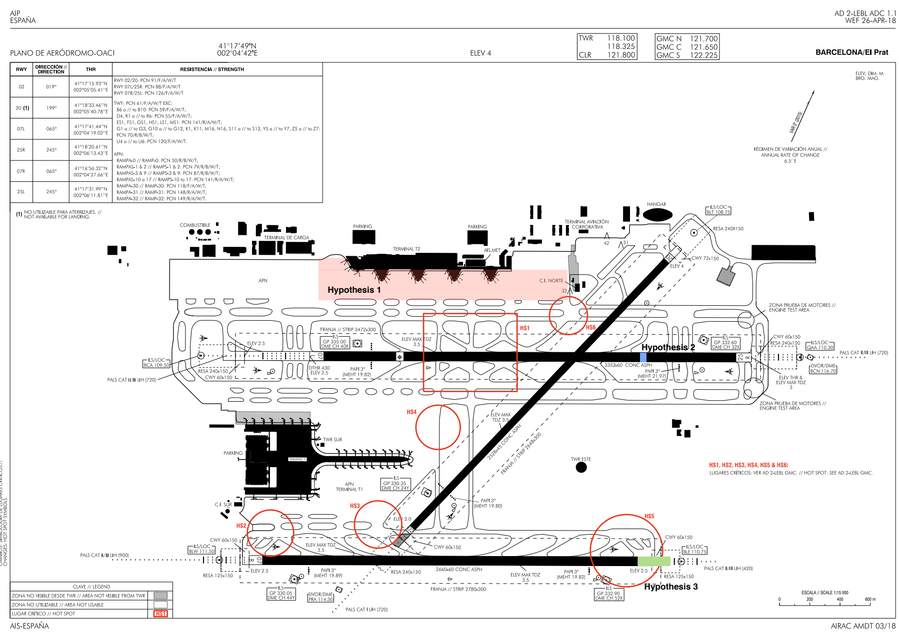

Fig. 23 - Plan of Barcelona El Prat airport with marked hypothesis (Attachment 1.)

Main characteristics and benefits of the PCPS Fort Miller Super Slab :

- Rapid installation
- Reduced weather related delays during construction
- 40 years service
- HSV testing up to 47 years estimated before failure under bad weather conditions for airfield pavement and up to 80 years before failure under standard weather conditions for highways (Kohler, 2016)
- Indoor casting in certified plant
- Higher initial costs offset by less construction and labour time and extended system life

(Attachments 2.,3.,4.) (Kohler, 2016)

Citation to support the benefits of the chosen method

"Based on the experience gained at the University of California Pavement Research Center (UCPRC), and from a literature survey of the other experiments, the precast concrete slabs systems (at least the ModieSlab® and SuperSlab®) have the potential to be long-life systems capable of adequately resist a great number of heavy traffic load repetitions (Van Dommelen 2004; DeLarrard 2006).

The following conclusions were derived from the experiment conducted by UCPRC for Caltrans in which a Dynatest Heavy Vehicle Simulator was used to test the structural performance of the Super-Slab system (Kohler et al. 2007).

1. The Super-Slab system of pre-cast slabs can be safely opened to traffic in the un-grouted condition, so that the panels can be installed in consecutive nights rather than completing the entire installation at one time. This allows for the old slabs to be removed and pre-cast slabs placed in position one night, and for completing the grouting procedure on the following night.

2. The life of this system of pre-cast slabs, when used as detailed for this test, is estimated to be between 142 and 242 million ESALs. These number results from estimated traffic applied in a section that did not fail, and a section that did fail under very high load levels. Taking as example highway I-15 in San Bernardino County, California, this number of ESALs could be assumed equivalent to more than 25 years of service, perhaps about 37 years before reaching failure.

3. The failure mechanism in this system of pre-cast slabs was no different than failure in cast-in-place jointed concrete pavements. Corner cracks, that are the result of loss of support, created conditions indicative of end of usable pavement life." (Tayabji, 2008)

6.4 Hypothesis 1 and analysis

H1: Reconstruction of an airside ramp currently in use is better to perform using the pre-cast method.

Introduction

The idea behind the Hypothesis 1 - to reconstruct an existing ramp pavement comes from the fact of what the airport itself represents. The privilege to use an aircraft is still for many people considered as something noble and representative. The airport transportation is in our minds often associated with traveling for business and for transporting goods for business purposes. Business is something considered and associated with standards and luxury. For this reason the environment where the representative act takes place should preferably also be representative and organized.

The desire to travel and discover also represents often something special and associates with the level of service and organization of traffic on point. Traveling for pleasure often represents the time where we leave our worries behind and are open to the new. It is also a desire for the airport to make their passengers feel at their best and deliver an adequate level of service. After all the airport is a reflection of the function of a country as it is the first thing a person gets into encounter with when arriving to the country.

Due to increasing number of people wishing and wanting to travel, airports have the tendency to expand and provide necessary capacities. Barcelona El Prat airport is no different. The question is if it is desirable to expand in opposition with reconstructing the existing and making in more efficient. This hypothesis bring into consideration to primarily rehabilitate the existing terminal instead of constructing a new one.

Also since we can only predict what the transportation industry will bring in the future, how will it develop, seeing all different and new means of transport for mobility, it should be desirable to construct in a more sustainable way which is open for possibilities of changing purpose in the future. Including all the high-tech today hardly imaginable loops that could transport us in minutes across the continents, it would be a question of a relatively short period of time to transform the mobility infrastructures.

The first ramps at Barcelona El Prat airport were build between 1948 and 1952 together with the third runway, taxiways and terminal building. It is a surface of 265 727m2 (selected area for analysis according to Fig.24). The area is constructed using a concrete pavement, probably dimensioned for a load of aircraft from the beginning of the aviation at El Prat airport. The pavement is currently suffering of extensive amounts of cracks caused by the load of parking aircraft. This surface is where the gate stands are and it connects the airside with the landside, in other words the passengers with the aircraft. In this area there are 30 stands to port the aircraft to connect it with the gate. The ramp is in sorrowful condition where the slabs are worn out, with many cracks, and hardly have a representative feel.

The functionality of the pavement is suffering under the load of aircraft and the Terminal 2 is currently being used only at 30% of the total airport traffic.

The solutions used at present, in case of big cracks, are to pour concrete or asphalt in cracks to repair them. This is a short term solution but is decreasing the life time of the pavement.

Scope determination

The idea is to preserve and increase efficiency and therefore capacity or to expand in terms of already available space to be ready and adaptable for the predictable increase of demand. To do so, we propose replacing the ramp pavement focusing on not interrupting the operations traffic. With present technologies the new pavement will provide long term durability and minimal maintenance.

For this kind of a replacement the important criteria is the large area. The time of construction and planning of the works are key in this case. We will evaluate this replacement using both pre-cast and cast-in-place methods to compare the difference.

Regarding the organization on site, the aspect of storing is necessary for the pre-cast method. For this hypothesis we suppose that there is sufficient surface that could serve as this temporary storage area. Regarding the cast-in-place, the concrete is usually mixed also at site (in fast term replacements) due to fast curing concrete. The areas necessary for storage are therefore similar. Depending on which segment is being replaced, the storage area would be variable. The estimated necessary area is to store approximately 50 panels at a time, which represents 5 shifts, so one week, with a standard working time and the new material could be brought on site every weekend, or in the beginning of the week.

The hypothesis is be to replace the old concrete pavement with the pre-cast concrete panels with characteristics of the Super-Slab® System (Att.2,3,4) and using Hormigon 48h for the cast-in-place method. These two examples have been chosen according to the availability on the market and data proving adequate test results of performance. Also to be able to create a comparable scenario in terms of time and cost. The reconstruction would take place in determined segments with according amount of panels. (Fig. 24) (Att.3.)

The area of the current situation of the ramp is an estimate from observation, which serves sufficiently for this hypothesis. From the estimated number of jointed slabs, the area is calculated, knowing that one slab has joints every 7m in each direction and therefore is $49m^2$. From the divisions showed in Fig.24 there are segments formed. The segments signify phases in which the slab replacement will take place. (Tab.4) The first 5 segments are chosen to divide the total area into parts with 6 fingers (stands) at the gate. The segments 6,7 and 8 are the division of the area without gate fingers. In Tab.4 we also calculate the amount necessary to be replaced for each method.

The Terminal T2 has a total of 30 finger stands at the gates and we suppose that they are used at 100% of their capacity, knowing that in reality only at peak hours they are being fully occupied. Therefore each division will reduce the operation of the terminal at 20% at peak hours. This is important because we need to introduce the lost profit from the closure of each segment.

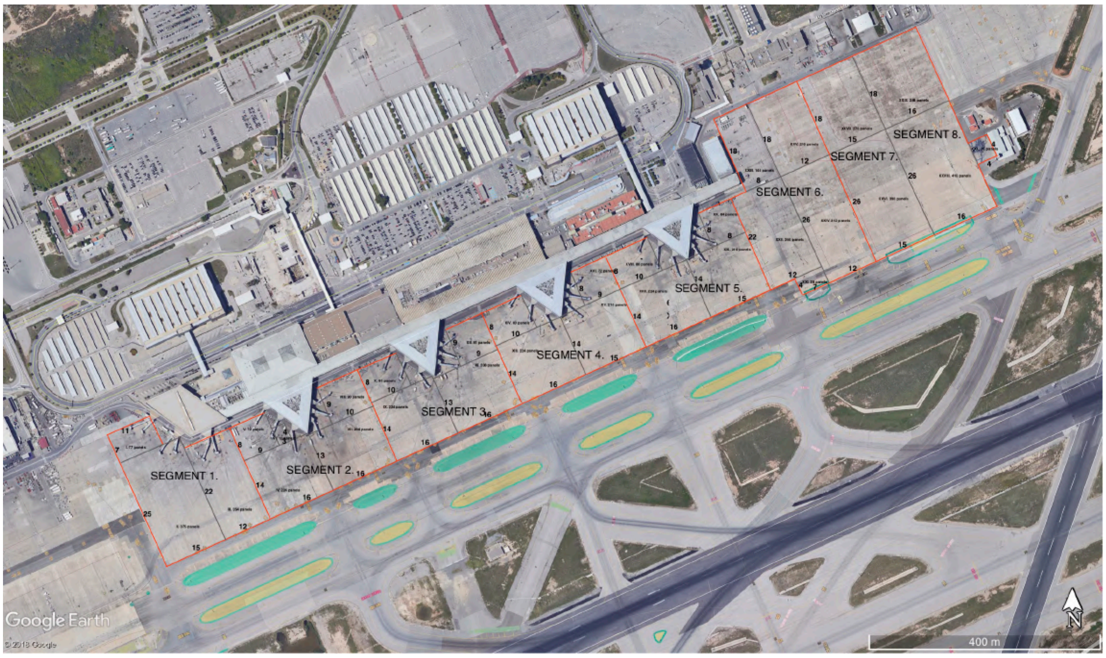

Fig. 24 : View of ramp surface at terminal T2 with represented hypothetical segments (GoogleEarth)

The goal is to prove that with the pre-cast method which is more expensive to invest in the beginning (in the first 10 years), the rapidity of the replacement overcomes the initial cost with lower lost profit on operations and that the durability will in the end result in lower total cost.

For the Cast-in-place method we have chosen a concrete mix from Lafarge company, Chronolia 48h. The reason is the availability at the Spanish market and experience with its usage. The prices are from the Spanish online database.(generadordeprecios.info, 2019) The Chronolia mix is a type of concrete with high initial strength and therefore can compete with the pre-cast panels at cases of fast track repairs. Its compressive strength after 48h upon installation is at 25MPa (Att.2.). This value corresponds to the minimal initial compressive strength of an airfield pavement (IPRF, 2003).

Tab. 4 : Segment division in Hypothesis 1 (Self Elaboration)

# of divisions for size estimation	# of jointed slabs (7x7m) 49m² current situation [Google Earth map]	m² per division	Segments (6 fingers closures)	m² per segment	# of panels pre-cast (4.57m x 3.96m x 0.225m) 18,1m² [source - HVS test]	m³ of concrete for cast-in-place method (thickness of pavement 300mm)
I.	77 pcs	3 773 m²	1.	35 084 m²	1 938 pcs	10 525 m³
II.	375 pcs	18 375 m²				
III.	264 pcs	12 936 m²				
IV.	224 pcs	10 976 m²	2.	29 694 m²	1 641 pcs	8 908 m³
V.	72 pcs	3 528 m²				
VI.	12 pcs	588 m²				
VII.	208 pcs	10 192 m²				
VIII.	90 pcs	4 410 m²				
IX.	224 pcs	10 976 m²	3.	29 057 m²	1 605 pcs	8 717 m³
X.	80 pcs	3 920 m²				
XI.	208 pcs	10 192 m²				
XII.	81 pcs	3 969 m²				
XIII.	224 pcs	10 976 m²	4.	28 714 m²	1 586 pcs	8 614 m³
XIV.	80 pcs	3 920 m²				
XV.	210 pcs	10 290 m²				
XVI.	72 pcs	3 528 m²				
XVII.	224 pcs	10 976 m²	5.	28 322 m²	1 565 pcs	8 497 m³
XVIII.	80 pcs	3 920 m²				
XIX.	210 pcs	10 290 m²				
XX.	64 pcs	3 136 m²				
XXI.	28 pcs	1 372 m²	6.	47 236 m²	2 610 pcs	14 171 m³
XXII.	264 pcs	12 936 m²				
XXIII.	144 pcs	7 056 m²				
XXIV.	312 pcs	15 288 m²				
XXV.	216 pcs	10 584 m²				
XXVI.	390 pcs	19 110 m²	7.	32 340 m²	1 787 pcs	9 702 m³
XXVII.	270 pcs	13 230 m²				
XXVIII.	416 pcs	20 384 m²	8.	35 280 m²	1 949 pcs	10 584 m³
XXIX.	288 pcs	14 112 m²				
XXX.	16 pcs	784 m²				

Introducing costs

To be able to compare the costs, we have to introduce the costs for a rigid pavement with combination with the Chronolia concrete mix. The price of the rigid pavement includes maintenance costs estimated for every 10 years related to appearing cracks and abrasion. As explained in the state of art of this thesis we will suppose the same duration for a cast-in-place pavement as a pre-cast pavement and therefore we suppose the estimated lifetime duration of Super-Slab® (Att. 3.) which is 40 years.

Tab. 5 : Construction costs comparison for period of 40 years (€/m²) (Self Elaboration)

Timeline	**Costs**	**10 years**	**10 years**	**10 years**	**10 years**	**Total per 40 years**
Cast-in-place	Demolition of the old pavement	€ 20				
	Debris transport off site until 10km (€4,55/m³, pavement 0,225m)	€ 1				
	Debris transport on site (€0,94/m³, pavement 0,225m)	€ 0				
	Stabilization of the sub-base and material for the sub-base	€ 27				
	Formwork installation and removal	€ 20				
	Rigid pavement cost with the use of concrete Chronolia 48h	€ 166				
	Maintenance (before discount)	(€ 22)	(€ 22)	(€ 22)	(€ 22)	
	Maintenance	€ 22	€ 16	€ 11	€ 8	
						€ 291
Pre-cast	Continous installation	€ 285	€ 0	€ 0	€ 0	
	Maintenance	€ 0	€ 0	€ 0	€ 0	
						€ 285

In Tab.5 we introduce the costs in comparison for the two methods. The costs for the cast-in-place method need to be introduced separately because they are not a part of the unit price for constructing the pavement. These costs are the demolition of the old pavement, debris transport on site and off site, stabilization of the sub-base, the price for a rigid pavement with the Chronolia 48h concrete mix (includes joint sawing) and formwork costs.

The costs for the cast-in-place method are described by items from the Spanish online database in the attachments of this thesis. (Att. 6.) (generadordeprecios.info, 2019)

For the maintenance costs (Tab.5) in the 40 years period, we introduce a discount rate of 3,5% due to decreasing value of the currency. D**t**=$1/(1+r)^t$ where r is the discount rate and t the number of years. (Ni, 2017)

D**t**= $1/(1+r)^t$ = 22×(1÷(1,035^10)) = €16 (for the first 10 years)

Tab. 6 : Pre-cast method - Estimated costs (Att.2) (Self Elaboration)

Repair type	Bid Price $ Per Sq. Yd.	Bid Price € Per m²	The average price for the analysis [per m²]
Intermittent	$244-$585	€185-€443	€ 314
Continous	$350-$401	€265-€304	€ 285

The costs for the pre-cast method include the removal of the old pavement and all transportation cost, the installation of the new pavement. The maintenance costs are close to none therefore the possible expense is included in the initial investment . (Att. 2.)

For the estimation of the construction speed for each method we use estimated values. For Super-Slab® it is listed in the attached brochure, converted. (Att.3,4) We account the possibility to replace 10 panels in the period of 8hours. For the cast-in-place method, we suppose that we are able to construct an area of 1000m² in 12hours (Mampearachchi, 2011)**.** To this time we of course need to add the 48h for curing concrete as stated by the 48h Chronolia concrete mix. (Att. 5.) The thickness of slab considered is 225mm. (Tab.7)

Tab. 7 : Speed of constructing using the two methods (Self Elaboration)

	Time for installation	Time for curing concrete	Total time	Amount installed (m²)		Speed of construction (m²/h)
Pre-cast	8 hours	0 hours	8 hours	10 panels of 18,1m²	181 m²	**22,63 m²/hour**
Cast-in-place	12 hours	48 hours	60 hours	500m x 2m	1 000 m²	**16,67 m²/hour**

For understanding the lost profit on operations we introduce the charges from the airport to the airline operating the aircrafts. We distinguish:

Aeronautical charges - charges at the Airside (for landing, terminal-area air navigation, passenger service at the terminals, cargo service, aircraft parking and hangars, security, airport noise, noxious emissions - air pollution, ground-ramp and traffic handling, en route air navigation)

Non-aeronautical charges - charges at the Landside, regulated by ICAO (commercial services, facilities at the airport, etc.)

Off-airport or non-operating revenue - charges not directly related to the airport (real estate, ventures, etc.)

In the Tab.8 we introduce the Aeronautical charge per one landing. In the point of view of the airport this presents the income which becomes a lost profit in case of closing a segment of the Terminal fingers for reparations.

For the Non-aeronautical charge we will consider an estimate of €16 per passenger (AENA, 2016). The data are from AENA annual reports. AENA is a Spanish public company founded in 2010 which is managing all the airports of general interest in Spain. The medium aircraft accommodates 200-300 passengers, for an estimate we consider 250pax/aircraft.

Tab. 8 : Aeronautical charges for landing medium aircraft at BCN El Prat airport (AENA, 2011)

Type of charge	cost (€)
BCN Air control at airport tax	€ 259
Landing	€ 548
Parking	€ 0
Security	€ 601
Passengers	€ 2 339
Fingers	€ 122
PRM service	€ 97
EASA	€ 92
Total	**€ 4 058**

Therefore we consider the total of €16x250= €4000 for the non-aeronautical charge per one landing. We will not consider the Off-airport or non-operating revenue for this analysis.

For this hypothesis we introduce the airport schedule of one day in the month of November. The reason is because November is one of the weakest months in terms of the traffic and therefore this would be a preferable period for the reparations of the pavement. The key is to interrupt the airport traffic as least as possible. The Terminal T2 has 6 fingers, therefore 6 segments will be directly affected by these charges.

From Tab.9 the number of landings operated by the Terminal T2 is 107 per 24 hours. With the charges for each landing we get a value of 107x(€4000+€ 4 057,79) = €862 183,53 per 24 hours.

Tab. 9 : Airport schedule 30/11/2019 (https://www.barcelona-airport.com/eng)

	Terminal T1 (ops./hour)		**Terminal T2 (ops./hour)**	
	RWY 07R/25L	**RWY 07L/25R**	**RWY 07L/25R**	**RWY 07L/25R**
Time of operations	Take-off	Landing	Take-off	Landing
0:00-1:00	0	11	0	3
1:00-2:00	1	3	0	0
2:00-3:00	0	1	0	0
3:00-4:00	0	0	0	0
4:00-5:00	0	0	0	0
5:00-6:00	0	1	0	0
6:00-7:00	17	2	11	0
7:00-8:00	27	5	7	1
8:00-9:00	5	8	3	6
9:00-10:00	14	15	6	9
10:00-11:00	13	16	13	9
11:00-12:00	18	22	7	10
12:00-13:00	16	17	6	9
13:00-14:00	10	8	10	6
14:00-15:00	13	13	2	1
15:00-16:00	14	10	1	7
16:00-17:00	13	13	9	8
17:00-18:00	13	14	5	4
18:00-19:00	10	13	5	3
19:00-20:00	10	14	9	7
20:00-21:00	14	13	2	4
21:00-22:00	3	6	5	5
22:00-23:00	2	7	2	3
23:00-0:00	2	9	1	12
SUM (# of ops./ 24 hours)	**215**	**221**	**104**	**107**

Tab. 10 : Total charges per one landing (Self Elaboration)

		20% of landings per 24hours		**Total**
Aeronautical charges	€ 4 058	21	€ 85 214	**€ 169 214**
Non-aeronautical charges	€ 4 000		€ 84 000	

This is the amount the airport would get at 100% capacity of the Terminal. Then the 20% represent 21 landings, 21 x (€ 4 000 + € 4 057,79) = **€ 169 213, 59** per 24 hours. This is the lost profit for closure of 6 fingers at the Terminal T2. (Tab.10)

Cost-effectiveness analysis

With the calculation of the speed of construction (Tab.7) and knowing charges that the airlines pay to the airport, we can evaluate the total amounts of lost profit. The lost profit is understood as the amount the airport would receive if there was no closure, with closure of each selected segment, the loss is 20% for the fist 6 segments but do not effect the segments 6, 7 and 8. In Tab.11 the comparison clearly shows the pre-cast method beneficial in terms of the lost profit. The difference in lost profit for the two methods is significant.

Tab. 11 : Analysis of Lost Cost in charges for each segment (Self Elaboration)

# of segment	Size of segment (m²)	Lost profit from Charges for closure of segment per day	Lost profit from Charges for closure of segment per hour	Time to construct segment with pre-cast (hours)	Lost profit - Pre-cast method	Time to construct segment with cast-in-place (hours)	Lost profit - Cast-in-place method
1.	35 084 m²	€ 169 214	€ 7 051	1 551 h	**€ 10 933 130**	2 105 h	**€ 14 841 724**
2.	29 694 m²			1 312 h	**€ 9 253 459**	1 782 h	**€ 12 561 571**
3.	29 057 m²			1 284 h	**€ 9 052 952**	1 743 h	**€ 12 289 640**
4.	28 714 m²			1 269 h	**€ 8 946 087**	1 722 h	**€ 12 144 569**
5.	28 322 m²			1 252 h	**€ 8 823 957**	1 699 h	**€ 11 978 772**
6.	47 236 m²	is not effected by the charges	is not effected by the charges	2 087 h	**€ 0**	2 834 h	**€ 0**
7.	32 340 m²			1 429 h	**€ 0**	1 940 h	**€ 0**
8.	35 280 m²			1 559 h	**€ 0**	2 116 h	**€ 0**

In the cost-effectiveness analysis we want to show that using the pre-cast method, the rapidity will save us the lost income from charges and is overall cheaper in investment. In Tab.12 we calculate the cost for reparation of the segments for both of the methods. The lost income depends on how long we will do the works for each method and therefore how long will the segment be closed. From this comparison we can see that the difference per one segment can be from over €1-€7million using the pre-cast method.

The Tab.12 proves that using the pre-cast method we will loose significantly less income than using the cast-in-place method. The initial investment is compensated with the overall saving of maintenance costs, which doesn't include additional costs for closures to perform maintenance.

Tab. 12 : Cost-effectiveness analysis of Lost Cost in charges and total costs (Self Elaboration)

# of segment	Pre-cast (€/m²)	Total Pre-cast (€/ segment)	Lost profit - Pre-cast	Cast-in-place (€/m²)	Total Cast-in-place (€/ segment)	Lost profit - Cast-in-place	Difference in cost € per segment	Difference in Lost profit € per segment
1.	€ 285	€ 9 998 940	€ 10 933 130	€ 291	€ 10 207 200	€ 14 841 724	**€ 208 260**	**€ 3 908 594**
2.		€ 8 462 790	€ 9 253 459		€ 8 639 055	€ 12 561 571	**€ 176 265**	**€ 3 308 112**
3.		€ 8 281 245	€ 9 052 952		€ 8 453 728	€ 12 289 640	**€ 172 483**	**€ 3 236 688**
4.		€ 8 183 490	€ 8 946 087		€ 8 353 937	€ 12 144 569	**€ 170 447**	**€ 3 198 481**
5.		€ 8 071 770	€ 8 823 957		€ 8 239 890	€ 11 978 772	**€ 168 120**	**€ 3 154 816**
6.		€ 13 462 260	€ 0		€ 13 742 655	€ 0	**€ 280 395**	**€ 0**
7.		€ 9 216 900	€ 0		€ 9 408 871	€ 0	**€ 191 971**	**€ 0**
8.		€ 10 054 800	€ 0		€ 10 264 223	€ 0	**€ 209 423**	**€ 0**
Total							**€ 1 577 366**	**€ 16 806 691**

Other criteria

The scenario of the Hypothesis 1, has explained the possibility of the replacement process of the existing pavement at Terminal T2 with both cast-in-place and pre-cast methods. It is important to state that we have evaluated this method in a continuous period of time, only considering an average of operations at the airport, using the data from a low season month, November. This means that for the purpose of this thesis it is not important to determine the minimal period possible to replace the pavement. This period could be shorter if the works where planned exactly in response to the statistically determined days of the airports lowest level of operations. For the purpose of the thesis we have showed that in comparison with the cast-in-place method, the pre-cast method is faster. To be more exact the difference is 5,96m²/ hour between the pre-cast and cast-in-place method. Since the pre-cast method allows for the pavement to be used right after segment placement, the segments could be planned in smaller areas and the terminal capacity wouldn’t have to be decreased to less than 20% considered in the analysis. Also we didn’t take into account that each segment with 6 fingers at the terminal gate is in reality burdened with different amounts of traffic during the months and days. For example in the peak hours, the middle segments are more occupied than the end segments. This was not included in the analysis because the cast-in-place method is not as variable due to its curing process, and it is less economical to replace smaller segments. In contrary the pre-cast method is ideal for smaller segment replacements, and therefore proves this as an advantage for this case.

The other parameters not considered are the weather conditions, on one side we are supposing that the works would be planned in the optimal weather conditions for each method, on the other hand the pre-cast method can be used at almost any weather (low and high temperatures compared to cast-in-place where the curing process needs appropriate conditions) and therefore this is another advantage not evaluated in the hypothesis.

There are almost no limitations in terms of the installation. Regarding the parameter of transportation, as this might seem difficult in the case of the heavy panels for the pre-cast method. The costs are included, and the difference in the end is not so significant from transporting concrete using heavy vehicles. Of course this depends on the distance of a concrete plant to the airport location. If the concrete plant is not near and the plan is to construct large amounts of pavement, the option of constructing a concrete plant at site should be considered. For the case of Barcelona El Prat airport, the nearest concrete plant is approximately 3km as shown in Fig.25. It is also in an industrial zone, therefore the transport should not have a big impact on the habitants. With the weight of the panels a permit for transporting heavy loads would be required. For the purpose of the thesis we suppose such permit would be granted. As for the cast-in-place, if we create the concrete mix on site, transportation of the components in big amounts is very similar.

Fig. 25 : Distance to the nearest concrete plant from Barcelona El Prat airport (GoogleEarth)

Conclusion

We have introduced a cost-effectiveness analysis where we are hypothetically looking to obtain the same product using two different methods. The most general result is to prove that the pre-cast method is more cost-effective compared to the cast-in-place method. If we introduce a more complex analysis, we would need to consider also the sensitivity analysis criteria. These criteria could be a sudden increase in price material, unpredicted delay of works, labour price change, sudden climate change, the end quality of the product. From the data obtained and used references we can already say how some of these criteria would affect the two methods. In general we know that in the construction industry time is of the essence and unpredictable events are very probable to happen. Usually we prevent these events by determining a financial reserve. Normally this reserve will cover some extra cost situations. Using the pre-cast method we can say that since we replace the curing process off-site, we already eliminate a part of the possibly problematic situations. Also the quality of the final product, in this case the prefabricate pavement panel, has a proven better quality in terms of the technical conditions, because off-site we have the time to test them more efficiently and the panel achieves full strength in supervised conditions as for the cast-in-place, the on site situation can be challenging in order to supervise the installation process of each segment.

In conclusion we have proven many advantages in favor of the pre-cast method in this hypothesis. In cases like this and similar, consisting of repairing or replacing a rigid concrete pavement, it is beneficial to use the pre-cast method. From the point of view of the cost but also in terms of maintenance, because the fact that we don't need to perform additional reparations can save additional costs from maintenance closures.

As it has been proven above, it is less time consuming and economically more advantageous to use the pre-cast method for airport ramp reconstruction. The Hypothesis 1 can be considered as confirmed.

6.5 Hypothesis 2 and analysis

H2: Replacement of a segment in an existing runway is more advantageous using the pre-cast method under condition of an exact knowledge of the original pavement composition (structure).

Introduction

The 24h use of the runways at todays European airport has a result of significant wear and tear of the surface also as the full depth of the construction. The idea to close the whole runway and repair it at once is in most of the cases an unimaginable solution for the airports. At Barcelona El Prat airport as previously stated the two runways work as segregated and therefore are necessary for the total capacity to maintain the number of operations. The idea is to replace a segment in the existing runway in order to maintain the functional properties and to interrupt the airport traffic as least as possible. The airport operates every hour and the peak hours understand up to 90 operations/hour. The idea is to choose the least frequent time to close the runway for an approximately 9 hour window. Also to redirect the other flights to the other runway if it is possible.

Scope determination

The area of the current situation of the runway RWY 07L/25R is taken from the data provided by the plan of the Barcelona El Prat airport (Att. 1.). The area is calculated with the overlap of the construction, because the plan shows only the used dimensions for the operations. The idea is to estimate a segment and make its replicability in an 9 hour time window which is the time of one shift + 1 hour and a time period that would influence the operations minimal. The extra hour is in order to perform the bituminous top layer necessary to connect the segment to the existing surface and for the technical aspect that we need to meet. (Novak, 2017), (Tayabji, 2016) The Tab.13 shows the current dimensions of the runway (60x3352m) and the dimension of the hypothetical segment 669m^2. The main idea is that the segment will be universal and it does not depend on its location throughout the runway surface. The Fig.26 shows only a hypothetical placement of the segment for this analysis but in reality the situation would be the same along the runway. The runway has to be completely closed during the segment and can not perform any operations due to security reasons and law. In Tab.13 we show also the number of pre-cast panels to replace the segment.

Tab. 13 : Runway RWY 07L/25R and the segment for Hypothesis 2 (Self Elaboration)

Runway classification name	Dimension of runway according to plan (Att. 1.)	Considered runway dimension with overlap (width each side +8m)	Dimension of selected segment	Area of selected segment (m^2)	# of panels for pre-cast method (4.57m x 3.96m x 0.225m) 18,1m^2 (Att.4.)
RWY 07L/ 25R	60m x 3352m	76m x 3620m	9.2m x 76m (width of segment for 2 panels)	699m^2	38 pcs

Since we have determined a time period for completing the works, we need to adjust the parameters of the methods cast-in-place and pre-cast, so that they can be performed. The goal is to prove that the pre-cast method can be used for this type of replacement and that it is more effective and cheaper.

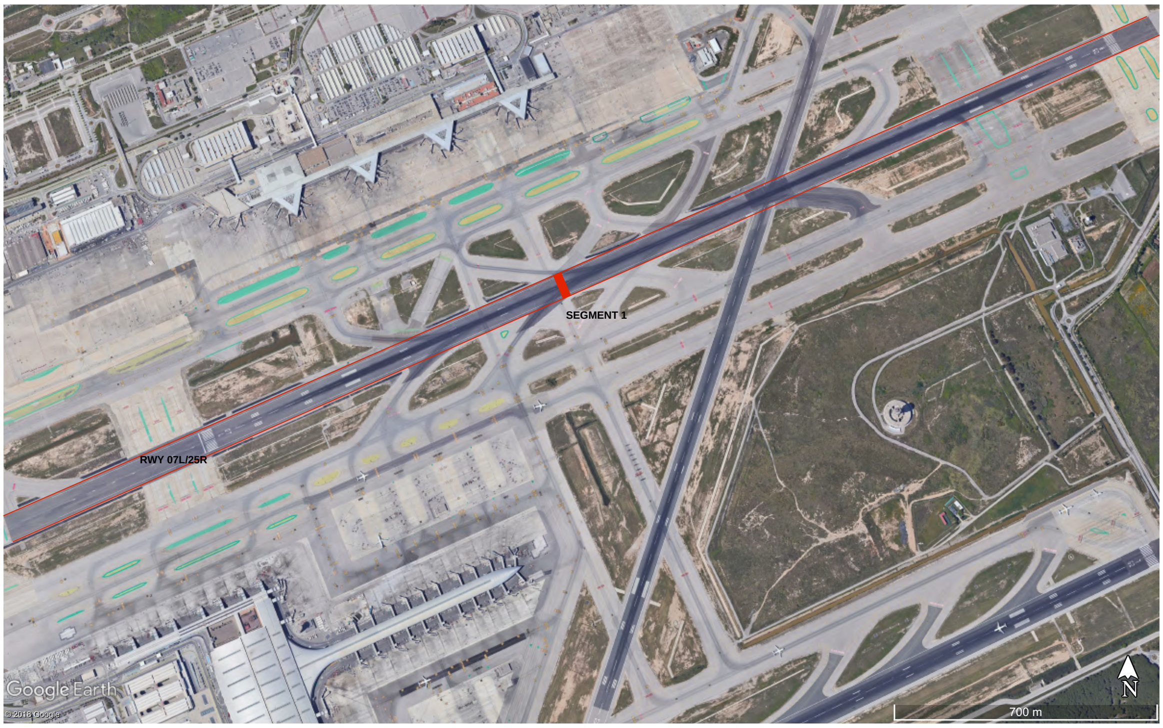

Fig. 26 : View of runway RWY 07L/25R surface with represented hypothetical segment (GoogleEarth)

As in Hypothesis 1, we will consider the low season for the operations of the airport which is November. The runway RWY 07L/27R operates all the landings and the take-off of large aircraft. In Tab.14 we show an 9 hour window for the proposed closure, selected due to the lowest number of operations. The time window is from 0:00 to 9:00 am. The total number of operations in this time period is 62.

To simplify we will suppose that during the period of closure the second runway (RWY 07R/27L) will work as a simple runway and will accommodate the Take-off also as the Landing of small and medium aircraft (columns 2,3 in Tab.14.). The second runway (RWY 07R/27L) is too short to accommodate the other take-off and landings therefore we suppose that this is the number of operation we need to cancel.

Tab. 14 : Airport schedule 30/11/2019 with selected 9h time window (https://www.barcelona-airport.com/eng)

	Terminal T1 (ops./hour)		**Terminal T2 (ops./hour)**	
	RWY 07R/25L	**RWY 07L/25R**	**RWY 07L/25R**	**RWY 07L/25R**
Time of operations	Take-off	Landing	Take-off	Landing
0:00-1:00	0	11	0	3
1:00-2:00	1	3	0	0
2:00-3:00	0	1	0	0
3:00-4:00	0	0	0	0
4:00-5:00	0	0	0	0
5:00-6:00	0	1	0	0
6:00-7:00	17	2	11	0
7:00-8:00	27	5	7	1
8:00-9:00	5	8	3	6
9:00-10:00	14	15	6	9
10:00-11:00	13	16	13	9
11:00-12:00	18	22	7	10
12:00-13:00	16	17	6	9
13:00-14:00	10	8	10	6
14:00-15:00	13	13	2	1
15:00-16:00	14	10	1	7
16:00-17:00	13	13	9	8
17:00-18:00	13	14	5	4
18:00-19:00	10	13	5	3
19:00-20:00	10	14	9	7
20:00-21:00	14	13	2	4
21:00-22:00	3	6	5	5
22:00-23:00	2	7	2	3
23:00-0:00	2	9	1	12
SUM (# of ops./ 24 hours)	**215**	**221**	**104**	**107**
Total ops./ closure 9h time window				**62**
Total ops. to be cancelled				**31**

By selecting the correct time period the impact of the cancelled flights is not significant (31 flights) and in reality some of the flights could be rescheduled to another time in the day. (Tab.14) Since for this hypothesis the time window is determined to be the same for the cast-in-place and pre-cast methods therefore we will not consider the impact of the cancelled flights. The lost profits would be the same for the two methods.

Introducing costs

For the pre-cast method, this time the costs to be considered are for the intermittent repair, because we start and deliver each segment separately. (Tab.15)

Tab. 15 : Pre-cast method - Estimated costs (Attachment 2)

Repair type	Bid Price $ Per Sq. Yd.	Bid Price € Per m^2	The average price for the analysis [per m^2]
Intermittent	$244-$585	€185-€443	€ 314
Continous	$350-$401	€265-€304	€ 285

For this hypothesis the situation of the costs is very similar to the Hypothesis 1. The difference is an extra bituminous top layer to create a composite pavement in combination with the concrete base, in order to be coherent with the rest of the pavement. There are additional costs for this layer and at the same time, it's life time duration is only 10 years before it has to be resurfaced. (Att.6.) So the cost is introduced every 10 years with a 3,5% discount rate. This time the choice of Chronolia concrete mix is considered Chronolia 15h (Att.5), because the time window is limited. Knowing that the opening strength would be in this small area sufficient, with the top bituminous layer, to open the runway and operate. The segment would achieve its complete strength in 15 hours. As consequence for a more complex composition of the concrete, logically the costs are higher. (Kohler, 2016), (Mampearachchi, 2011)

The analysis shows a possible scenario in case that the current structure is suitable with the concrete structure. Due to insufficient data on the composition of the pavement of the runway at Barcelona El Prat airport it is hard to determine this possibility of reparation. In the Att.1. the classification number PCN tells us that the RWY 07L/25R consists of a flexible pavement type. The supposed composition regarding other European runways, does include a concrete base layer. On the other hand, there are some European airports that use the Rapid Set CSA Cement concrete for runway reparation, which classifies as a cast-in-place method. For example the London Heathrow airport and pre-cast components (csacement.com, 2019), (Pre-cast components, 2019). Also in the paper (Kohler, 2016) the Super-Slab® has been tested by the Heavy Vehicle Simulator as an airport pavement. Other airport examples have been mentioned in part 4.3 of this thesis.

Tab. 16 : Construction costs comparison for period of 40 years (€/m²) (Self Elaboration)

Timeline	Costs	10 years	10 years	10 years	10 years	Total per 40 years
Cast-in-place	Demolition of the old pavement	€ 20				
	Debris transport off site until 10km (€4,55/ m³, pavement 0,225m)	€ 1				
	Debris transport on site (€0,94/ m³, pavement 0,225m)	€ 0				
	Stabilization of the sub-base and material for the sub-base	€ 27				
	Formwork installation and removal	€ 20				
	Rigid pavement cost with the use of concrete Chronolia 15h	€ 219				
	Maintenance (before discount)	(€ 22)	(€ 22)	(€ 22)	(€ 22)	
	Maintenance	€ 22	€ 16	€ 11	€ 8	
	Bituminous top layer	€ 15	€ 11	€ 8	€ 5	
	Maintenance bituminous layer	€ 2	€ 2	€ 1	€ 1	
						€ 389
Pre-cast	Intermittent installation	€ 314	€ 0	€ 0	€ 0	
	Maintenance	€ 0	€ 0	€ 0	€ 0	
	Bituminous top layer	€ 15	€ 11	€ 8	€ 5	
	Maintenance bituminous layer	€ 2	€ 2	€ 1	€ 1	
						€ 359

Cost-effectiveness analysis

We can see (Tab. 16) that overall the total cost per m² is lower for the pre-cast method in the 40 years of duration. If we compare only the initial cost in the first 10 years the cast-in-place method is in favor. The difference of €5 per m² is not a significant difference. This factor should be also overcome by the fact that the cast-in-place method requires higher maintenance costs and therefore would require additional closures of the runway.

In Tab.17 we analyze the difference in cost, that shows benefit in using the pre-cast method. The difference would bring a saving but the difference is not as significant. If we compare the results to the Hypothesis 1, introducing the lost profit is a significant factor in construction of large segments.

Tab. 17 : Cost-effectiveness analysis of the segment for the two methods (Self Elaboration)

# of segment	Size of segment (m²)	Pre-cast (€/m²)	Total Pre-cast (€/segment)	Cast-in-place (€/m²)	Total Cast-in-place (€/segment)	Difference in cost € per segment
1.	699 m²	€ 359	€ 251 076	€ 389	€ 271 804	**€ 20 729**

Other criteria

If we suppose that the idea of this hypothesis would be planned for an exact day, and therefore the weather could be pretty accurately predicted and therefore should not present a threat factor in the construction. For this case the sensitivity criteria like in Hypothesis 1, should not be as influencing in this example. For example, regarding a sudden price change is not likely because of the immediate short duration construction operation.

The scenario of the Hypothesis 2, shows the cost advantages for the pre-cast method. It is limited by the real composition of the pavement in order to be able to coexist with the replaced segment. The cost-effectiveness analysis is based on the goal to achieve long duration of pavement and low maintenance necessity in order not to interrupt the airport traffic.

Conclusion

For the purpose of this thesis the conclusion is that we cannot say if this option is possible without knowing the exact composition and thickness of the runway. Since the considered segment is variable and can be placed anywhere in the runway, it has to be verified first that it will be able to coexist with the existing structure. Additional testing might be required. (Similar to (Kohler, 2016)) . Theoretically if replacing the segments with the goal of transforming the whole runway into a rigid structure, there would be a determined plan of the works and it could be possible to apply this method. In this case, where the hypothesis is to replace the segments according to their wear and tear in an irregular order the performance is questionable. On the other hand, if tested and approved, the possible cost saving advantages comparing cast-in-place were proven.

As it has been proven above, replacement of a segment in an existing runway is more economically beneficial using the pre-cast method under condition of an exact knowledge of the original pavement composition (structure). The Hypothesis 2 can be considered as confirmed.

6.6 Hypothesis 3 and analysis

H3: Extending an existing runway is more advantageous using the pre-cast method under condition of an exact knowledge of the original pavement composition (structure).

<u>Introduction</u>

The increasing demand of the airport transportation is creating logical pressure on the airports to increase their capacities. In Barcelona El Prat airport there are an estimate of 47 million passengers that need to be served every year, but this number is set to be increasing into 50 million passengers per year in no longer than a few years. (Fig.20.) For this reason the current amount of runways is not sufficient and therefore an extension of the small runway is to be planned.

In this hypothesis the scenario is to perform an extension of RWY 07R/25L, with the smallest impact on the operations of the airport. (Fig. 27) In order to extend a runway, we have to close the runway for the entire time of the construction. According to the law, the runway can not operate if not completely prepared for the operations. This means that since the runway does not consist only of the pavement itself but also from a complicated lighting system which is spread on each end of the runway, so the whole construction has to be technically prepared for an operation of landing or take-off. Even though the length of the extension is over 600m, it is not possible to start the construction on the side that is not connected to the runway surface, before closing the whole runway. Knowing this, closing the runway presents a substantial aspect in the total airport capacity. At this moment the runway RWY 07R 25L operates around 30% of the airport traffic which is significant for the airport income. (barcelona-airport.com, 2019). The challenge will be how to perform this extension and influence the traffic at Barcelona El Prat airport as least as possible.

Fig. 27 : View of runway RWY 07R/25L surface with represented extension (GoogleEarth)

Scope determination

The dimensions of the runway and the extension segment are showed in Tab.18. (Att. 1) Also the calculated area and number of panels needed for the extension.

Tab. 18 : Runway RWY 07R/25L and the extension segment for Hypothesis 3 (Self Elaboration)

Runway classification name	Dimension of runway according to plan (Att. 1.)	Runway dimension after extension	Dimension of extension segment	Area of extension segment (m^2)	# of panels for pre-cast method (4.57m x 3.96m x 0.225m) 18,1m² (Att.4.)
RWY 07R/ 25L	60m x 2660m	60m x 3352m	60m x 692m	41 520m²	2 281 pcs

We will assume a situation, where in the time of the closure of the extending runway, the total traffic will be rearranged to be operated by the two remaining crossing runways RWY 02/20 and RWY 07L/25R. From Tab.19 we calculated the percentage capacity of the operations handled by the runway RWY 07R/25L. It is 33% but in the case of a reorganization of the airport traffic according to the new capacity (during the extension closure), the third runway will be used and therefore will lower this percentage estimation. For the purpose of this thesis we will assume that the airport capacity that will be lost due to the closure will be 25%.

Similar to the Hypothesis 1, we have to include the lost capacity in the values of the lost profits for charges from the airlines to the airport. We will consider the same aeronautical and non-aeronautical charges as in Hypothesis 1. (Tab.20) Therefore the total lost charges per one day of closure are more than €1M.

Tab. 19 : Airport schedule 30/11/2019 (https://www.barcelona-airport.com/eng)

	Terminal T1 (ops./hour)		Terminal T2 (ops./hour)	
	RWY 07R/25L	**RWY 07L/25R**	**RWY 07L/25R**	**RWY 07L/25R**
Time of operations	Take-off	Landing	Take-off	Landing
0:00-1:00	0	11	0	3
1:00-2:00	1	3	0	0
2:00-3:00	0	1	0	0
3:00-4:00	0	0	0	0
4:00-5:00	0	0	0	0
5:00-6:00	0	1	0	0
6:00-7:00	17	2	11	0
7:00-8:00	27	5	7	1
8:00-9:00	5	8	3	6
9:00-10:00	14	15	6	9
10:00-11:00	13	16	13	9
11:00-12:00	18	22	7	10
12:00-13:00	16	17	6	9
13:00-14:00	10	8	10	6
14:00-15:00	13	13	2	1
15:00-16:00	14	10	1	7
16:00-17:00	13	13	9	8
17:00-18:00	13	14	5	4
18:00-19:00	10	13	5	3
19:00-20:00	10	14	9	7
20:00-21:00	14	13	2	4
21:00-22:00	3	6	5	5
22:00-23:00	2	7	2	3
23:00-0:00	2	9	1	12
SUM (# of ops./24 hours)	**215**	**221**	**104**	**107**
100% of the operations (total SUM)				**647**
ratio of operations between runways	**33 %**		**67 %**	
25% of the total capacity	**162**		485	

Tab. 20 : Total charges per one landing per one day (Self Elaboration)

		25% of the total capacity		**Total per one day of closure**
Aeronautical charges	€ 4 058	162	€ 656 382	**€ 1 303 382**
Non-aeronautical charges	€ 4 000		€ 647 000	

Introducing costs

Next we select the price of the pre-cast panel placement. For this hypothesis the segment will be closed for the whole extension period, therefore we are talking about a continuous repair. (Tab.21)

Tab. 21 : Pre-cast method - Estimated costs (Attachment 2)

Repair type	Bid Price $ Per Sq. Yd.	Bid Price € Per m^2	The average price for the analysis [per m²]
Intermittent	$244-$585	€185-€443	€ 314
Continous	$350-$401	€265-€304	€ 285

As for the cast-in-place costs, they are introduced in Tab. 22. The items are similar to Hypothesis 1, with the additional bituminous layer. The concrete mix for the cast-in-place method is Chronolia 48h because of the comparable costs and time performance.

Tab. 22 : Construction costs comparison for period of 40 years (€/m²) (Self Elaboration)

Timeline	Costs	10 years	10 years	10 years	10 years	Total per 40 years
Cast-in-place	Demolition of the old pavement	€ 20				
	Debris transport off site until 10km (€4,55/m³, pavement 0,225m)	€ 1				
	Debris transport on site (€0,94/m³, pavement 0,225m)	€ 0				
	Stabilization of the sub-base and material for the sub-base	€ 27				
	Formwork installation and removal	€ 20				
	Rigid pavement cost with the use of concrete Chronolia 15h	€ 166				
	Maintenance (before discount)	(€ 22)	(€ 22)	(€ 22)	(€ 22)	
	Maintenance	€ 22	€ 16	€ 11	€ 8	
	Bituminous top layer	€ 15	€ 11	€ 8	€ 5	
	Maintenance bituminous layer	€ 2	€ 2	€ 1	€ 1	
		€ 274				**€ 336**
Pre-cast	Continuos installation	€ 285	€ 0	€ 0	€ 0	
	Maintenance	€ 0	€ 0	€ 0	€ 0	
	Bituminous top layer	€ 15	€ 11	€ 8	€ 5	
	Maintenance bituminous layer	€ 2	€ 2	€ 1	€ 1	
		€ 303				**€ 330**

The compressive strength has to be at least 25MPa at opening such large segment of the runway. In Tab. 22. the initial costs are compared in the 40 years time period. In favor of the pre-cast the total costs are smaller.

For calculating the speed of construction (Tab.23.) we will consider the time of 9 hours for the pre-cast method, same as in Hypothesis 2. For the cast-on-place the time is same as in Hypothesis 1, 12 hours for placement, 48hours for curing but with the additional 1h for placing the bituminous layer.

Tab. 23 : Speed of constructing using the two methods for Hypothesis 3 (Self Elaboration)

	Time for installation	Time for curing concrete	Time for bituminous layer performance	Total time	Amount installed (m²)		Speed of construction (m²/h)
Pre-cast	8 hours	0 hours	1 hour	9 hours	10 panels of 18,1m²	181 m²	**20,11 m²/hour**
Cast-in-place	12 hours	48 hours	1 hour	61 hours	500m x 2m	1 000 m²	**16,39 m²/hour**

<u>Cost-effectiveness analysis</u>

From here we can evaluate both methods analyzing the duration of the construction and evaluating the lost profits. From Tab. 24 it is clear that the pre-cast method is in favor in terms of the time of the construction. The difference of lost profit between the two methods is significant, more than €25M.

Tab. 24 : Analysis of Lost Cost in charges for Hypothesis 3 (Self Elaboration)

Size of segment (m²)	Lost profit from Charges for closure of segment per 24h	Time to construct segment with pre-cast (hours)	Time to construct segment with pre-cast (days)	Lost profit - Pre-cast method	Time to construct segment with cast-in-place (hours)	Time to construct segment with cast-in-place (days)	Lost profit - Cast-in-place method	Difference between methods
41 520 m²	€1 303 382	2 065 hours	86 Days	**€ 112 119 613**	2 533 hours	106 Days	**€ 137 545 850**	**€ 25 426 237**

The hypothesis is similar to Hypothesis 2, supposing that the composition of the runway pavement will be able to coexist with the proposed pavement. In this case it is more likely because the segment is continuous and therefore has only one side that has to be attached to the existing runway. The scenario could be performed using a new method of pre-cast components consisting of beams and panels that are assembled on site and grouted. (Pre-cast components, 2019) It the listed reference such pavement runway composition is supposed to be the future most efficient construction method for rapid construction of new ramps, taxiways and runways at airports. The pre-cast elements in this system are smaller than the pre-cast panels used to evaluate this hypothesis (Att. 2,3,4) and therefore the final price could be cheaper if ordered in large quantities.

In Tab.25 we evaluate the overall difference in costs between the two methods. We have found out that the total cost is about €200 thousand cheaper in the overall period of 40 years for the whole runway extension. Observation is that any closure of the runway for longer period of time, has significant impact on the airports income from the charge costs.

Tab. 25 : Cost-effectiveness analysis for Hypothesis 3 (Self Elaboration)

Size of segment (m²)	Total Cost - Pre-cast method (€330/m²)	Lost profit - Pre-cast method	Total Cost - Cast-in-place method (€336/m²)	Lost profit - Cast-in-place method	Difference between Total Cost	Difference between Lost profit
41 520 m²	€13 705 333	€ 112 119 613	€ 13 934 775	€ 137 545 850	**€ 229 441**	**€ 25 426 237**

Other criteria

In this hypothesis, we did not estimate the time necessary to perform the other works related to the extension, for e.g. the installation of the lighting system adjacent to the runway. We suppose this would be performed simultaneously with the construction of the pavement.

The scenario of the Hypothesis 3, has explained the possibility of constructing the required extension of the runway RWY 07R/25L with both pre-cast and cast-in-place methods. The condition is to perform a connection between the current runway and the new extension in order for the runway to perform required technical properties. This hypothesis is evaluated in a continuous period of time, only considering an average of operations at the airport, using the data from a low season month, November. This means that for the purpose of this thesis it is not important to determine the minimal period possible to perform the extension. This period could be shorter if the works where planned exactly in response to the statistically determined days of the airports lowest level of operations. The main criteria is that the closure has to be performed in one continuous period, because the runway can not be used if not complete and properly enlightened with the lighting systems.

The sensitivity criteria for this hypothesis regarding the weather conditions have not been included, but the Spanish yearly average temperatures are always suitable for pre-cast repair. The high summer temperature could present some limitations in terms of the cast-in-place method. Regarding the transport the situation is the same as for Hypothesis 1 with the addition of the top layer bituminous material.

Other criteria like a sudden increase in price material, unpredicted delay of works, labour price change, sudden climate change, the end quality of the product, can appear in this scenario, but the impact would be similar for the two methods and it can not be evaluated with an exactly determined time period.

Conclusion

Same as for the whole thesis, using the pre-cast method we eliminate a part of the possibly problematic situations, due to redirecting the curing process off-site. Also the quality of the final product, in this case the prefabricate pavement panel, has a proven better quality in terms of the technical conditions, because off-site we have the time to test them more efficiently and the panel achieves full strength in supervised conditions as for the cast-in-place, the on site situation can be challenging in order to supervise the installation process of each segment.

In conclusion of this hypothesis, and knowing the results of Hypotheses 1 and 2, we could say that the pre-cast method is something to be considered in case of large amounts of pavement replacements in time pressing conditions. From the theoretical part of this thesis we can also say that small segment replacements of same composition pavement are suitable for the pre-cast method.

As it has been proven above, extending an existing runway is faster and more economically beneficial using the pre-cast method under condition of an exact knowledge of the original pavement composition (structure). The Hypothesis 3 can be considered as confirmed.

7. Conclusion

We have proven that there are advantages to using pre-cast method in airport construction. In this thesis we have summarized the various ways how to rehabilitate or construct an airfield pavement. It is important to say that all of these methods can be currently used and each has its benefits. The choice must be made according to the criteria that each airport requires, depending on what part of the airfield needs to be constructed or rehabilitated. It also depends on the amount of traffic operated on the airport which can be in some cases the main decision aspect, because the time of a closure can create great economical loss. With the current trend of increasing traffic and the consequent increasing of airport capacities, the time of construction is essential. We must also consider the factor of the growth of the traffic from a sustainable point of view for the future. We can predict the growing number of customers up to many years based on past data but there are many factor that could turn around the predictions and reform the air traffic. At the present, the predictions used in the thesis considered for a 40 years period could be accurate to the current situation.

The estimated time period of 40 years was used simply to illustrate and explain the ideas in this thesis. In reality it is hard to estimate a time period for the future, because we can not predict how the mobility segment of air traffic will change. Currently the air transport has an insecure future, as its main aspects are high fuel consumption and high emissions of CO_2. This transport method is not considered as ecological, and therefore research is concentrated to modify or change this transport for the better. On the other hand the number of passengers is still increasing and therefore the general strategies of airports are to increase their capacities to satisfy this demand.

The first part of the thesis is a thorough research of the different existing methods for the construction of pavements or other infrastructural elements. Different types of pavement construction are explained depending on the technical aspect of load replacement, which is related to the airport construction where this is a significant criterion. With a SWOT analysis, in Chapter 3.2 we have proven that for its expected long term durability the pavement is more favorable and more sustainable to use the concrete pavements. Examples of use of these pavements are also discussed in the theoretical part. Further-on, the available methods of cast-in-place and pre-cast for constructing a pavement are explained. Advantages and disadvantaged of the two methods are also presented from a technical point of view in this part of the thesis.

In the second part we introduce a case study of Barcelona El Prat airport to show possible application of the pre-cast method in comparison with the cast-in-place method. The second part is structured into discussions over raised hypotheses where we propose possible scenarios of rehabilitation and new construction of airport pavements.

Overview and results of the three raised and confirmed hypotheses:

H1: Reconstruction of an airside ramp currently in use is better to perform using the pre-cast method.
As it has been proven above, it is less time consuming and economically more advantageous to use the pre-cast method for airport ramp reconstruction. The Hypothesis 1 can be considered as confirmed.

The first hypothesis is focused on the ramp (also called apron) at the Terminal T2, where serious degradation of the existing pavement has been detected. The proposed solution compares replacement of this pavement in segments to reduce the impact of closures for construction on the terminal operations. The result of this scenario shows that the time savings, using the pre-cast method, have a significant impact on the financial loss from each day the segment of the terminal is not operating. The initial investment cost is slightly higher for the pre-cast method. On the other hand there are many advantages to it, mainly that the segments` rehabilitation can be performed separately and therefore with efficient planning of the closures, the financial loss could be reduced to minimal amount if the right timing/season of the year is chosen.

H2: Replacement of a segment in an existing runway is more advantageous using the pre-cast method under condition of an exact knowledge of the original pavement composition (structure).
As it has been proven above, replacement of a segment in an existing runway is more economically beneficial using the pre-cast method under condition of an exact knowledge of the original pavement composition (structure). The Hypothesis 2 can be considered as confirmed.

The second hypothesis proposed an intermittent reparation of a runway segment using the pre-cast method. The result of this analysis has a condition, that the specific composition of the pavement must be well known before the commencement of works. The insufficient available information on the pavement composition and the interaction with the pre-cast or cast-in-place panels questions the validity of this hypothesis. In order for the new segment to be properly functional with the existing pavement, the new segments` layers have to be adjusted to it. Supposing that the pre-cast and the cast-in-place methods are suitable, an analysis is made to prove that the pre-cast method brings cost savings in the longterm. At the same time these cost saving are not as significant as in the discussion regarding Hypothesis 1, because the construction is not influenced by the lost profit.

H3: Extending an existing runway is more advantageous using the pre-cast method under condition of an exact knowledge of the original pavement composition (structure). As it has been proven above, extending an existing runway is faster and more economically beneficial using the pre-cast method under condition of an exact knowledge of the original pavement composition (structure). The Hypothesis 3 can be considered as confirmed.

The third hypothesis is based around the planned extension of one runway at the airport. In case of extending a runway at an airport, its closure impacts the total airport capacity. Therefore the duration of the closure is essential for the volume of the lost profit from the airports` limited operation capacity. The result of the performed analysis proves that with the time savings using the pre-cast method, the lost profits are significantly reduced. The difference is in dozens of millions euro and could therefore present a significant decision criterion. Until this day, the lost profits from extension closures have been probably compensated with the higher income after the realization due to the increased capacity. This hypothesis similarly depends on the composition of the pavement as does the Hypothesis 2, but in this case, there are new types of the pre-cast method already being developed for runway construction. It consists of a system of pre-cast components that are assembled on site forming a better load transferring pavement than any currently used methods available on the market. It is a method suitable for all ramps, taxiways and runways of the airport.

The pre-cast method can be considered as the method with the great potential of the fast construction for the airports to respond the increasing capacity demand. This mentioned potential is analyzed and evaluated in this thesis, because although the pre-cast method has been already scarcely applied, there are still many more opportunities that should be explored with this method. This thesis therefore tries to raise the discussion regarding the use of this method in the infrastructural construction. It presents an opportunity for time and cost savings and together with its other advantages could simplify future pavement construction and rehabilitation in many aspects.

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