MAKING BIG THINGS MOVE
RETRACTABLE STADIUM ROOF
GROUP 12

THE TEAM

Matt Thompson
Why is this a good solution and design?
This design incorporates the use of Trusses with a lightweight membrane which allows the roof to be retracted quickly and easily with only little power needed. This negates the need for large, expensive motors which will be prone to malfunctions and maintenance whilst still allowing the roof to function and protect the entire pitch (120 x 70). This also prevents large amounts of noise from the operation of it which will make a much more pleasant experience for the spectators.The design is a unique one having never been done before so would pose as a tourist attraction drawing people to the stadium and increasing revenue from the stadium massively. The actual design limits the amount of steel used and so is a much more environmentally friendly approach than other methods which would involve a full steel roofing system. The use of latest technology in sensor and battery technology means that safety is put at the heart of the design as well as efficiency as the roof will be unable to open in weather which may prove too inclement whilst still producing an enjoyable attraction.

Zhounan Wang
What risks does the project carry and what are we doing to address them?
The risks are divided into three parts: design risk construction risk and moving risk. Risks from design part are basically about the wrong calculation and wrong selection of the material and the actuators. Construction risks are the dangers in the construction, including tripping falling at heights or Electric leakage.
To address them, HAZOP analysis and RAG analysis are used to analyze the frequency, causes, consequence, measures to mitigate risks and make a security rating.

Yufei Wang
How can it be improved?
The intensity of the design will no longer be a major target for improvement, as the environment in port Elizabeth in South Africa is environmentally friendly and there is no extreme weather. In the whole system, due to the fine design of gear system in the support, it is difficult to maintain in the event of failure, which will be the direction we will consider in the future. At the same time, how can it prolong its service life, facilitate the replacement of equipment and maintenance, and also be the direction should to be considered in the future

Adam Waring
What will be the impacts of the roof on the wider world?
As can clearly be seen from our Sulitest (add diagram) results, we are clearly ahead of the world benchmark in every field, and we aimed to implement this into our design where sustainability was at the forefront. Therefore, the impacts of the roof on the wider world will be to firstly raise awareness of the need for sustainable development. This should be delivered through making it very public the fact that the materials being used have come from recycled materials and will be being recycled when it comes to the end of their use. Also, the fact that all of the energy used in the opening and closing of the roof has come from sustainable resources should be advertised.

Naworn Waradilok
What is its true cost, who will pay and who will profit?
Nelson Mandela Bay Stadium used to host the FIFA World Cup in 2010 and Africa Cup of Nations in 2013, which can guarantee that this stadium is outstanding and creditable for the event organizer and sport organizer. By improving the fixed roof to the retractable roof, it will cause a three-positive impact. First, the owner of the stadium: Because the stadium can use at all weather condition, which lead to the increasement in event. Second, Audience: More comfortable while using the stadium. Because the audience don't need to be worried about the rain. Third, Villager who live near the stadium: Can attract grab attention from not local audience due to the new design of the roof, which can impact the money flow in local seller.

Hang Xu
What will be the impacts of the roof on the wider world?
Another impact for the stadium will be boosting tourism in the Eastern Cape and in South Africa as a whole. At the moment around 8% of all foreign tourists to South Africa visit the Eastern Cape and only 6% spend at least one night in the province. (Compiled by NMMU Tourism Research Unit from SA Annual Tourism Report 2005).A roof on the Nelson Mandela Bay stadium will increase the number of events that can be held there, and subsequently boost the number of people visting the city and province for tourist reasons. Not only will this help the tourist industry but also the many small independent businesses in the area.

01 Communication and Knowledge Integration

01. Port Elizabeth – South Africa background

Political – ANC current political party embroiled in corruption charges since Jacob Zuma's resignation in 2018 meaning political turmoil could affect client's ability to continue to fund the project as well as potential changing client which may ask for alterations to original design.
Economic – Restricted growth due to economic imbalances (only 1.5% in 2018) meaning any project must be value for money as well as achieving all aims and having little/no requirement for expensive maintenance.
Climate - As shown from *Figure 1* the average annual maximum temperature is: 22.0° Celsius with an average annual minimum temperature is: 13.0° Celsius this suggests a warm climate all year round which presents its own problems in that any roof structure must be breathable to be under when in use and there must be a consideration of the thermal expansion of materials used as well as potential overheating problems with motors/generators exposed to direct sunlight. This was found when analysing the Warsaw 2012 Euro stadium which had problems with breathability when deployed, hence steps will such as leaving gaps between the membrane and roof structure and temporary roof to allow air circulation must be taken. The amount of rainfall for South Africa is quite temperamental as some months have much heavier rainfall than others hence it is important for any structure to have appropriate drainage facilities for heavy rainfall. Snowfall is incredibly rare however a small factor must be considered when taking loads for the ULS.

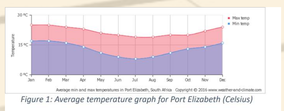


Figure 1: Average temperature graph for Port Elizabeth (Celsius)

Figure 2: Rainfall for South Africa last year note the heaviest rain in November

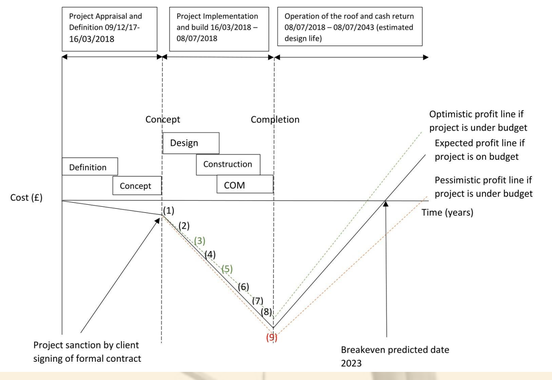
Environment – Port Elizabeth is on the South African coast and hence presents two challenges one due to the large South Westerly with an average wind speed of 6.9 m/s hence any structure must be designed taking this into account. Another factor is the potential corrosion not only from the salt spray from the coast but also the pollution from the manufacturing in the city meaning pitting corrosion will play a factor in the design life of the steel used. The type of soil is an important factor in design as its ability to take load and allow the movement of plant to and from the site is a large issue for a project this site. An issue in the original building of the stadium was that vehicles failed to find traction in the soft soil and so the construction of temporary paths was needed to allow the movement of heavy plant. A similar approach will also have to be used in this project to prevent accidents and near misses.
Construction – South Africa has a wealth of natural resources meaning most can be locally sourced at a reasonable price promoting economic growth and value for money of the project. This is as well as having a skilled local workforce meaning all the contracts can be awarded to local contractors preventing potentially costly foreign contracting.

02. Problem analysis

	Qualitative	Quantitative problem assessment
Civil	The roof must support its own weight without excessive bending or deflection during normal use as this will unnerve spectators as well as being resistant to potentially excessive loading criteria which may arise. The structure must be ergonomic to withstand the large wind speeds which arise in Port Elizabeth a poorly designed structure could risk large wind loads which could undermine its stability. The structure must be aesthetically pleasing to be effective as an attraction as well as a functional work as well as having a low maintenance requirement as the height of the structure will make any maintenance costly and potentially dangerous. Due to its proximity to the coast the structure (particularly loadbearing cables) must be protected against pitting corrosion due to the higher percentage of salt in the air.	Deflection of members must not be as much as L/200 under SLS loading used as an assessment of failure criteria. Total price of materials must be within £500 million to ensure client value for money, The span of the roof must at least cover the entire pitch 70 x 120 m^2 and the central pin must have a minimum height of 40 m to prevent interference with play or the existing stand structure.
Mechanical	The motors and rails must be water and dustproof due to the weather conditions in Port Elizabeth as describe earlier. Also the motors must be able to withstand salt erosion from the nearby sea. The motors must be efficient as possible to help complete the SDGs and to save money for the customer. Due to high temperatures a cooling system will need to be fitted to prevent over heating in the motors.	The roof must have a run time of under 7 minutes to ensure usefulness for the customer. Must also be able to open and close in high wind speeds of up to 20m/s
electrical	Because of the regular rainfall and rainy days, the maintenance of electronic modules should be considered. Using Block-based design so that each Block can be easily replaced once broken. Chips and coils in each Block should be cover by waterproof coating such as P2i. In addition, coils should not be exposed to the air directly because the water vapor would cause corrosion and influence the electricity transfer efficiency.	The loads are DC motor, so that the industrial electricity (3 phase 380V AC 50Hz) need to be convert to DC. Because of the using of battery, the problem need to change into charging battery by industrial electricity. It is necessary to build a power supply system to convert the 380V AC power into high voltage DC power which Tesla Motors2, the electric vehicle company, have already doing for years.

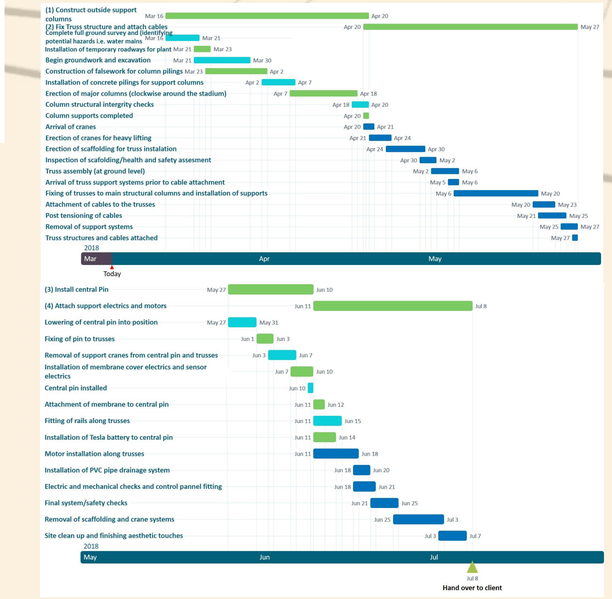
02 Project Management

01. Task Breakdown



Task Breakdown (each task represents a major activity which must be signed off by the relevant party):
(1) 16/03/18 Start date for the build external surveying team will be hired and RFO (Request for Information) filed to energy/water companies in Port Elizabeth regarding location of gas/water/electric piping and cable locations
(2) Approval of subcontractor for excavation renting of heavy plant for piling excavation and importing of concrete mix materials to be mixed on site and beginning of piling construction.
(3) Erection of steel support towers which will be pre-cast and arrive on site no later than 07/04/2018 and be erected and have all relevant safety checks performed by site Engineer no later than 20/04/2018
(4) Fixed base crane hires and construction (from external subtractors), whilst pre-cast truss structures are moved onto site and relevant welding performed by qualified personnel with Arc welders and signed off by the site Engineer 02/05/2018
(5) 05/05/2018 Wheeled support vehicles arrive on site to support each truss as each cable is hydraulically post tensioned with all support vehicles removed by 27/05/2018 pending full inspection any delays will affect critical path length.
(6) 27/05/2018 Lowering of central pin into position begins using a team of contracted fitters pin should be attached no later than 31/05/2018 allowing for the instalment of basic electrics by 10/06/2018
(7) 11/06/2018 Pin undergoes fitting of PVC Type 3 membrane, Tesla battery, motor system and drainage pipes by qualified personal in each field (Tesla battery will be fitted by company employees) the expected end date for fitting installation is 21/06/2018
(8) 21/06/2018 Final system checks involves firstly major contractor inspections of sub-contractor work on all elements from 27/05/2018 checked by site Engineer, this will then be inspected by an independent representative of the client with an expected final approval date of 25/06/2018
(9) 25/06/2018 Removal of all temporary works and scaffolding and all plant/cranes not necessary for final tidy up to be removed by 03/07/2018 when site clean-up will begin and finish by 07/07/2018 with final handover date 08/07/2018

02. Time Line



03 Sustainability

01. United Nations Sustainable Development Goals 2030

Goal	Aims	How
7 AFFORDABLE AND CLEAN ENERGY	• By 2030, increase substantially the share of renewable energy in the global energy mix. • By 2030, double the global rate of improvement in energy efficiency.	• Only using clean energy to open and close the roof. • Raising awareness for the need for clean energy in Port Elizabeth.
8 DECENT WORK AND ECONOMIC GROWTH	• Promote development-oriented policies that support productive activities, decent job creation and creativity. • By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products.	• Bringing jobs through increasing the variety and number of events that can be held at the stadium, and the requirement for maintenance and upkeep of the roof. • The new events that held in the stadium will bring vast numbers of people to Port Elizabeth, boosting tourism and helping local businesses.
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	• By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse.	• Through the recycling and reuse of as many materials as possible in the building and maintenance of the roof

02. Exact Method

The energy required by the roof is given by the following equation:
7 x 60 x 200 x 16=1,344kJ
This will all be supplied by our **clean energy supplier**, POWERX.

POWERX
AFRICA'S ENERGY EXCHANGE

Using the following companies for recycling:

REDWOOD MATERIALS
The batteries used in the roof can be recycled by companies like TESLA and REDWOOD

ROOFCOLLECT® Recycling System for Thermoplastic Membranes
ROOFCOLLECT can separate the useful PVC compounds from the PVC membrane.

WASATCH METAL RECYCLING
Companies like WASATCH can recycle up to 93% of the steels used.

Long Life Cycle Materials:
After looking at the Warsaw stadium case study it was found that the PVC membrane can be used for up to 30 years with maintenance. The steel beams can last up to 100 years (sustainable bridge case study). Therefore after replacing the PVC membrane every 30 years the roof should be able to last up to 100 years.

04 Health and Safety

HAZOP Analysis – Construction
Activity:

NO	HAZARD	HAZARD EFFECT	SEVERITY	PROBABILITY	RISK	MINIMISE RISK BY	RESIDUAL RISK
1)	Tripping/falling at heights	1)Minor injuries- death	H	H	H	1)Introduction of harnesses working at heights this is defined at any height over 4 m	M
	Plant crash/accident	2)Crush of limbs, broken bones and damage to machinery	H	M	H	2) Construct temporary roads and keep all plant on them through enforced guidelines	M
2) 3)	Electric Leakage	3)Electrocution	H	L	M	3) Check electric circuit and equipment regularly. An expert must supervise the equipment using and if possible, cut down the power when workers working.	L
4)	Asbestos	4)Serious breathing difficulties	H	L	M	4) Survey from fully trained external contractor and workers must wear breathing sites inside of potential asbestos zones	L/E
5)	Noise from plant	5)Long term hearing difficulties	M	H	H	5) Plant can only work between the hours of 9am-11pm and ear protection must be worn inside specified zones	L
6)	Falling objects	6)Potential head injuries	M	H	H	6) Helmets must be worn on site and toe boards installed on scaffolding	L
7)	Unearthing water/electric mains	7)Power cuts/water shortages and potential electrocution and large costs for repairs	H	M	H	7)Use of full geotechnical survey using ultrasound /other techniques to be carries out before excavations over 0.45m can begin	L
FINAL ASSESSMENT: As long as site staff are fully safety briefed and trained risk will be at sufficiently low level to allow all planned works to go ahead.					OVERALL RISK:		L/M

HAZOP Analysis –Operation
Activity:

NO	HAZARD	HAZARD EFFECT	SEVERITY	PROBABILITY	RISK	MINIMISE RISK BY	RESIDUAL RISK
1)	Motor overheating	1)Failure of motors to operate potential fire hazard	L	L	L	1)Regular motor maintenance by trained personnel and sensors fitted which can detect overheating	L
2)	Falling from heights during repairs	2)Potentially deadly falls	H	L	H	2) Use of harnesses when working at heights and no repairs during extreme conditions	L
3)	Cable corrosion	3)Potential sudden failure of cables causing major failures	H	H	H	3) Use of plastic protection for steel as well as protective painting before use	M
FINAL ASSESSMENT: Structure will be safe if regular monitoring of cables takes place					OVERALL RISK:		L

RISK ASSESSMENT MATRIX

PROBABILITY \ SEVERITY	Catastrophic (1)	Critical (2)	Marginal (3)	Negligible (4)
Frequent (A)				
Probable (B)		Falling objects	Noise from Plant	
Occasional (C)	Tripping falling at heights, Cable corrosion	High wind speed unbalancing people/plant		
Remote (D)	Excavations hitting electric/water mains	Plant crash/accident	Motor over heating	
Improbable (E)	The leak of electricity		Asbestos	
Eliminated (F)				

01. Risk Analyse Conclusion

Risk analysis is essential to ensure a safe and healthy work environment. It allows our group to identify our project's threats in construction and then we can handle the potential risks and avoid the problems. By using the HAZOP (Hazard and Operability Study) in our project, it helps our group identify the potential accidents and its causes, consequences and solutions are identified effectively. Furthermore, Red Amber Green (RAG) helps to identify likelihood and consequences for each risk. Using this method, it is visually easier to identify which risks matter the most. For example, from the risk assessment matrix, it shows that the most serious potential problems are that people tripping falling at heights and falling objects. Both could cause injuries or even death and danger to the construction. After analysis these problems, these issues can be easily avoided by using the harnesses working at height and wearing the helmets all the time as soon as starting to work. Therefore, these serious problems will be easily avoided. The risk analysis can make a safe environment and make the construction effective.

05 Enterprise

01. PEST Analysis

The aims of this project is to build the retractable roof structure for Nelson Mandela Stadium, which is located in the South Africa. By using the PEST analysis method, it can be classified into four main point: Political, Economic, Socio-Cultural and Technological.

Political	Economical	Socio-cultural	Technological
-Tax for foreign owner company 20%. -Minimum wage for domestic worker is 13.05 ZAR per hours, which is 0.80 pound (03/06/18). -Maximum working hours 45 hours per week (5 days per week). -Over time rate is 1.5 time of the hourly rate and not more than 10 hours/week. -Import tax fees is 14%	-Inflation in south Africa is 4.27 %, which is keep decreasing over 10 years. -Electricity cost 8.46 cents per kilo-Watt hour (0.061 pound). -Diesel cost 13.78 ZAR per litre (0.84pound). -Unemployment rate of south is 26.7% (01/31/18). -Economic growth in Africa is 3.1% (01/31/18).	-Population 55.91 million, which is totally enough for the labour force. -Population growth rate 1.6%. -The retractable roof can attract more customer from all over the place. -The stadium can increase the number of event. Because the new roof stadium can use at all of the weather condition.	-Servo motor is flexible with many kind of works. -Advance in technology of construction such as prebuild structure or Prefabrication part. -From the advancement of the motor production, The motor will have long lifespan and more durable.

02. Budget Analysis

Material Cost Table

List	Part Name	Supplier	Quantity	Price/Unit (£)	Price/Quantity (£)
1	Servo Motor	3X Motion Technologies Co., Ltd	16	1,425	22,800
2	Driving gears	Rargears	64	164.83	10,549.12
3	Gear boxes	Yilmaz UK Ltd	16	552	8,832
4	Wheels	BIL Group Ltd	448	112.54	50,417.92
5	Top Chord	Speedy Metals	3,569	1,070	3,818,830
6	Bottom Chord	Speedy Metals	3,569	1,540	5,496,260
7	Connecting Chord	Speedy Metals	3,569	1,070	3,818,830
8	Support Cables	Certex Group	380	3,500	1,329,962
9	Cable Protector	ArcelorMittal	906	60 per kg	54,344
10	Membrane	ArcelorMittal	8,400	80 per m^2	672,000
11	PVC Piping	Poly pipe	210	349.99	73,497.9
	Overall Cost				15,356,322.94

Project Budget Table

List	Cost Labels	Price in ZAR	Price in Pounds
1	Material Cost	254,565,500.82	15,356,322.94
2	Import Tax Fees (14%)	35,639,170.11	2,149,885.21
3	Labour Cost (8 months 1,800 people)	33,825,600	2,073,600
4	Over Time labour Cost (8 months 1,800 people)	11,275,200	691,200
5	Income Tax for foreign owner company (20%)	26,115,754	1,621,498.64
6	Profit 30%	130,578,774.2	8,107,493.27
	Total Budget	492,000,000.00	30,000,000.00

By analyse the PEST table, it will show some important data, which is effect to the total budget. By combining material cost table and overall project budget table, the total budget need to set around 32,000,000.00 pounds, which will give about 30% for profit.

06 Conceptual Design

Concept Design History 01

The original design idea was novel in its uniqueness which to use 4 columns with high tension cables connecting to and supporting a central pin which would be counterweighted by with anchor cables connected to concrete anchors working in a similar way similar to how a suspension bridge supports a load. The membrane bearing cables would then be tied and pretensioned to the already constructed stadium roof which currently shelters the stands. This was rejected as this would require such large support columns it would be impractical, the already constructed roof structure would not take the extra tension of the membrane supporting cables and the anchor cables would have to be at such an angle that the anchors would interfere with nearby structures and car parks.

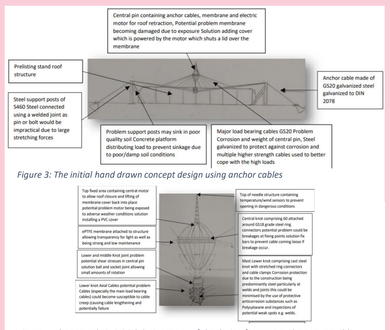


Figure 3: The initial hand drawn concept design using anchor cables

Figure 4: The central pin initial design many of the design features such as retractable membrane cover was carried over to concept design 3

Concept Design History 02

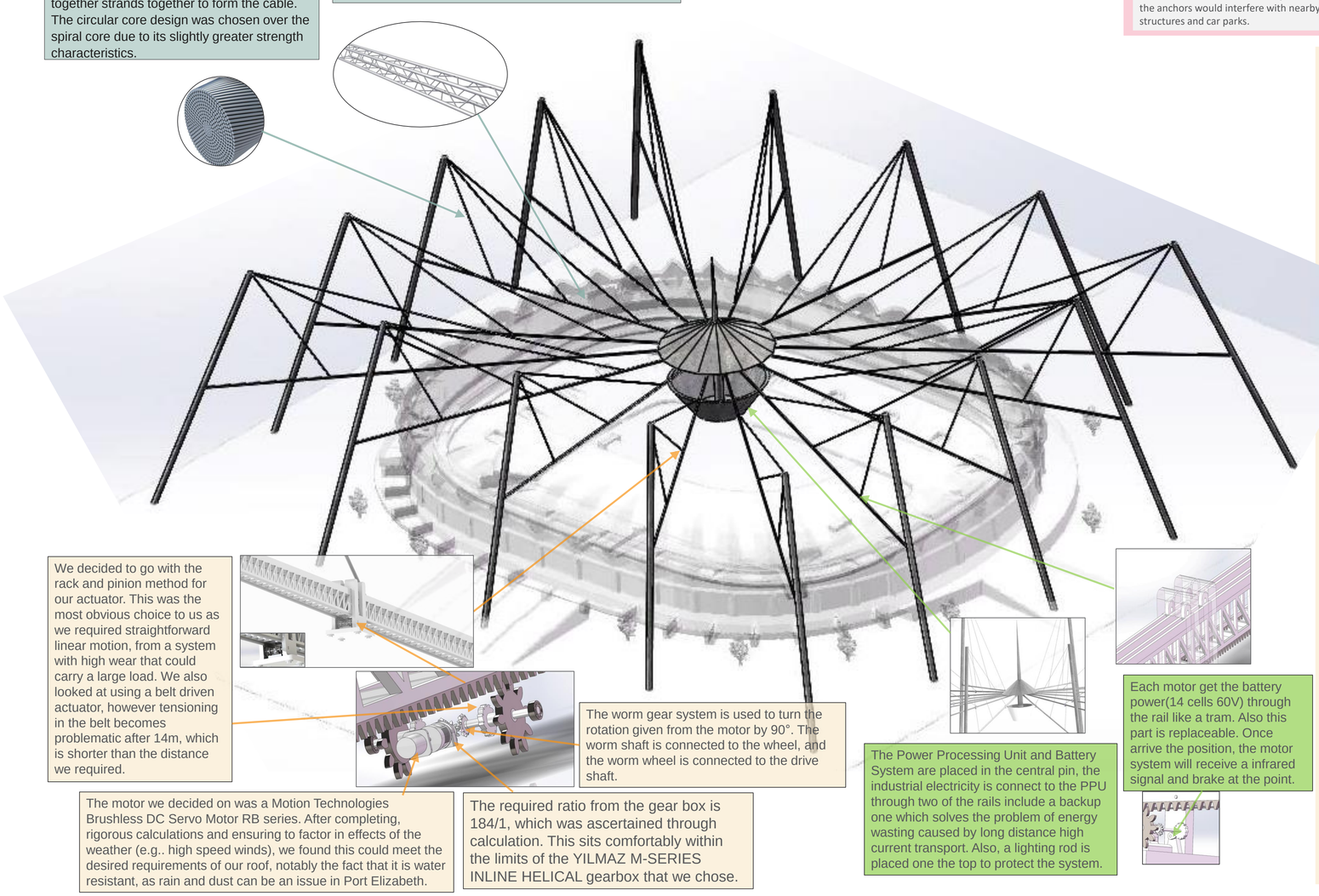
The second idea represents a more developed approach than the first and after some research an idea based on the Warsaw Euro 2012 stadium and the Commerzbank arena retractable roof was formed. This revolved around the use of a compression ring similar to that used on a bike tyre which would ring around the stadium with multiple high-tension wires projecting from it towards the central pin. This idea had the upsides of being extremely lightweight and incredibly innovative ignoring the need for large steel structures and having the advantage of being used on a larger scale than the technology had ever been used before. The reason this idea was discarded was that the complexity would prove too large and the structure would be beyond the scope of what was calculable.


Figure 5: Spoke and wheel structure similar to concept design 2

Figure 6: Warsaw 2012 Euro stadium was a string influence on our design with features such as the addition of sensors and even the construction methods adopted having a big influence on our concept ideas

The major load bearing cables used will be large structural cables these steel cables are composed of individual S460 steel circular cables which are twisted together and glued together using a polymer glue. These individual interlocking steel then stick together strands together to form the cable. The circular core design was chosen over the spiral core due to its slightly greater strength characteristics.

For the main load bearing trusses, a Warren truss was chosen for its ability to span the large gaps which would be required of it and perform well under UDL's. As its equilateral triangle shape allows a much more even distribution of loads than other trusses based on right angle triangles such as the Pratt truss.



We decided to go with the rack and pinion method for our actuator. This was the most obvious choice to us as we required straightforward linear motion, from a system with high wear that could carry a large load. We also looked at using a belt driven actuator, however tensioning in the belt becomes problematic after 14m, which is shorter than the distance we required.

The worm gear system is used to turn the rotation given from the motor by 90°. The worm shaft is connected to the wheel, and the worm wheel is connected to the drive shaft.

The motor we decided on was a Motion Technologies Brushless DC Servo Motor RB series. After completing, rigorous calculations and ensuring to factor in effects of the weather (e.g.. high speed winds), we found this could meet the desired requirements of our roof, notably the fact that it is water resistant, as rain and dust can be an issue in Port Elizabeth.

The required ratio from the gear box is 184/1, which was ascertained through calculation. This sits comfortably within the limits of the YILMAZ M-SERIES INLINE HELICAL gearbox that we chose.

The Power Processing Unit and Battery System are placed in the central pin, the industrial electricity is connect to the PPU through two of the rails include a backup one which solves the problem of energy wasting caused by long distance high current transport. Also, a lighting rod is placed one the top to protect the system.

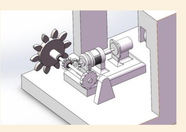
Each motor get the battery power(14 cells 60V) through the rail like a tram. Also this part is replaceable. Once arrive the position, the motor system will receive a infrared signal and brake at the point.

03. The final design

The final structure relies on trusses at a projected 5˚incline towards a central point; supported by cables projected outwards from 16 towers located around the outside of the stadium which all meet at a central point. The trusses act as a vessel for the PVC membrane carrying rail and motors as well as supporting the weight of the central pin and roof once in use.

Why this design?
This solution is a much easier to calculate model which utilises the trusses ability to ignore torsional and bending moment effects and focus on designing members for tension and compression, whilst also keeping the movable part of the roof at a minimum weight of only 82 kN for the entire membrane. The employment of extreme high strength cables (to minimise excess weight) along the length of the truss support the bulk of the weight and prevent any sagging which may occur due to the large spans involved in the design; with the largest truss being 144.1 m long.

Mechanical-The umbrella shaped roof has 16 rails directed outwards from the centre. On each rail there are 7 roof supporters fixing the roof and the outermost supporter contains a servo motor with a gear box connected to a worm gear system, as can be seen in figure below. This powers the driving gear along a rack and pinion actuator and moves the roof in or out. The whole process of opening or closing the roof should take under 7 minutes, and we have chosen parts that make this possible.

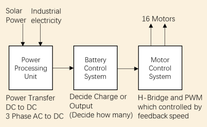


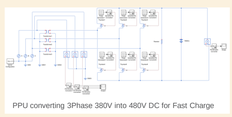

04. summaries of the discipline-specific designs

Civil-The main structural design consists of 16 columns encircling the stadium which pointing upwards from the ground at an angle of 75° and reaching a horizontal height of 70m. From these 16 cable supported Trusses at a 5° incline to the horizontal converge on a central point at the l centre of the stadium and hold up the central pin; which acts as a housing for the roof membrane when not in use. When in use the membrane is extended along rails which run along the trusses and expands to cover the entire playing field of 120 x 70 m^2

A cross section of the design

Electrical-The electrical part of the project is to provide power for servo DC motors and design a control system for the motors. The main idea of the electrical part design is to separate the whole challenge into power converting(using industrial electricity and solar power to charge the battery) and DC output controlling(using the battery voltage to drive the motor and adjust motor speed by changing the output voltage of the battery), by adding a battery system into the central pin as a entrepot. This design can easily reduce the difficulty of the maintenance and fault finding in terms of it separates a complex system into two concise system – battery charging and DC circuit, in another word, the system is similar to a remote-controlled toy car. For the battery choosing, considering about the weight, energy capacity and price, 2170 battery, which is also used by Tesla and Samsung, is one of the appropriate choice.




PPU converting 3Phase 380V into 480V DC for Fast Charge