DEVELOPEMENT OF CABLE FESTOON CALCULATION TOOL FOR CRANE ELECTRIFICATION.

Lappeenranta–Lahti University of Technology LUT

Electrical Engineering, Master's thesis.

2023

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Examiner(s): Professor Pasi Peltoniemi

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ABSTRACT

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LUT School of Energy Systems

Electrical Engineering

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Development of Cable Festoon calculation tool for Crane Electrification.

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Keywords: Crane electrification, Cable festoon.

The development of different technologies in cranes demand for a robust and reliable crane electrification system. The advancement in technology facilitates the companies to upgrade the existing systems with new products to satisfy the needs of the modern-day customer.

The master's thesis is a study of the cable festoon system developed by Konecranes for crane electrification. The study includes the development of a calculation tool to design the cable festoon system for overhead cranes. The calculation tool would help the designer find the most optimal solution that satisfies all design constraints. The thesis also compares the advantages and limitations of crane festoon system with other electrification systems to understand the significance of adapting to the new system.

ACKNOWLEDGEMENTS

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A special thanks to my parents for being the source of inspiration. Last but not the least, thank you to all my dearest friends for always having my back, supporting me with everything I do.

The time that I spent in Konecranes and LUT University has been the golden years in my career as well as on a personal level. The entire journey has taught me to take roots in being myself. There is a long way to go and with such great people around me, I will never stop aiming higher.

Vishaal Pillai.

SYMBOLS AND ABBREVIATIONS (may be included, but not relevant for all theses)

Roman characters

A	Frame height	[mm]
H_r	Loop height from beam	[mm]
K_b	Cable package width	[mm]
L_B	Cable length at bridge end	[mm]
L_{BU}	Cable length at building end	[mm]
L_C	Total length of cable	[mm]
$L_{CT\,MAX}$	Cable trolley complete length	[mm]
L_{CT}	Length of cable trolley	[mm]
L_E	Length of End clamp	[mm]
L_F	Festoon cable length	[mm]
$L_{G\,DEF}$	Defined Gathering Length	[mm]
$L_{G\,MIN}$	Minimum Gathering Length	[mm]
LH_{MAX}	Maximum loop height from beam	[mm]
Li	Traversing distance	[mm]
L_s	Binding Distance	[mm]
L_T	Towing side length	[mm]
L_{TT}	Length of towing trolley	[mm]
$L_{W\,MAX}$	Maximum distance between suspension fittings	[mm]
Law	Distance between suspension fittings	[mm]
P	Tension factor	[mm]
R_{CT}	Radius of Cable trolley	[mm]

$S2$	Thickness of largest cable	[mm]
St	Cable package height	[mm]
v	Speed	[m/min]
Wc	Weight of cable package	[kg/m]
W_{CT}	Load per cable trolley	[kg]

Dimensionless quantities

N	Number of cable loops
N_{CT}	Number of cable trolleys

Abbreviations

CFD	Computational Fluid Dynamics
GA	General Arrangement
UTP	Unshielded Twisted Pair
WLAN	Wireless Local Area Network

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1 Introduction

In the Industry 4.0 era the cranes have been modernised in such a way that the human involvement can be reduced, and the efficiency of production can be improved.(Yang *et al.*, 2022)

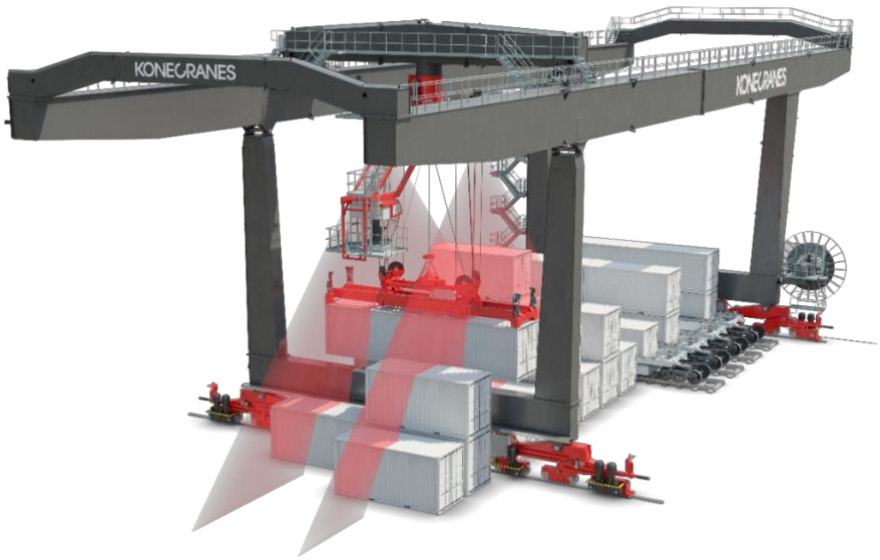

Figure 1. Safety assist feature (Image credits: Konecranes).

The above image illustrates a Konecranes port crane equipped with smart features to place the shipping containers carefully at the desired location without human errors. The speed of operation and reliability of the crane has a direct impact on the productivity and profits of the organisation. The addition of new components in the crane layout that executes the smart features demands for a more advanced crane electrification system. Moreover, Cranes are also used in places with harsh environments like mines, nuclear power plants and extreme temperature areas. The surrounding environmental conditions have a major impact on the electrification system and several factors need to be taken into consideration before deciding the crane electrification system(Keane, Schwarz and Thernherr, 2013).Additional safety measures must be taken for cranes used in explosion proof environments. Therefore, a reliable electrification system which is more suited for the modern-day needs is the preferred choice.

1.1 Objective

To satisfy the design needs of the modern cranes and to increase the company profits, Konecranes decided to develop and utilise their own cable festoon system for crane electrification. The objective of the thesis is to study the cable festoon system designed and manufactured by Konecranes and come up with the calculation formulas to design the cable festoon in customer projects.

The designing of cable festoon system cannot be achieved with trial-and-error method by choosing random number of components and cable loop as there are various design constraints that needs to be taken into consideration. The focal point of the thesis is seeking the optimal solution during cable festoon designing to ensure structural stability and to avoid ordering excess components needed to design the festoon system. The thesis would provide the information to understand the working of cable festoon system, the various terminologies, and the method to design it.

The thesis also compares the benefits and limitations of the cable festoon system with the existing crane electrification technologies. This study would help the company take a more informed decision regarding the implementation of the product in future projects.

1.2 Structure of the thesis

The first two sections of the thesis are the literature review of the crane electrification systems, their limitations, and the reasons to adopt a new crane electrifications system.

Section 3 gives a detailed description of the construction and working of Cable festoon systems. It also mentions the various parameters for designing the cable festoon system. The results involve the procedure to utilise the calculation tool on a customer project and the festoon system has been designed for that project.

Finally, the research is concluded with the summary of the thesis and suggestions for future research.

2 Cranes

Cranes have been used for loading and unloading application in construction sites, material handling factories and manufacturing plants(Wu and Xia, 2014). Due to the type of application and other factors like location, space constraints, environmental factors there has been tremendous development in the cranes sector which led to several types of cranes. The thesis is focused on the Electrification of Overhead cranes.

2.1 Motions of a Crane

The crane has multiple moving components which needs to be constantly connected to the power source for operation. To develop the electrification system of the crane it is necessary to consider the travelling motion of the different parts of the crane. To explain the general working principle of the crane motions, the various working directions of the Overhead crane has been explained in detail.

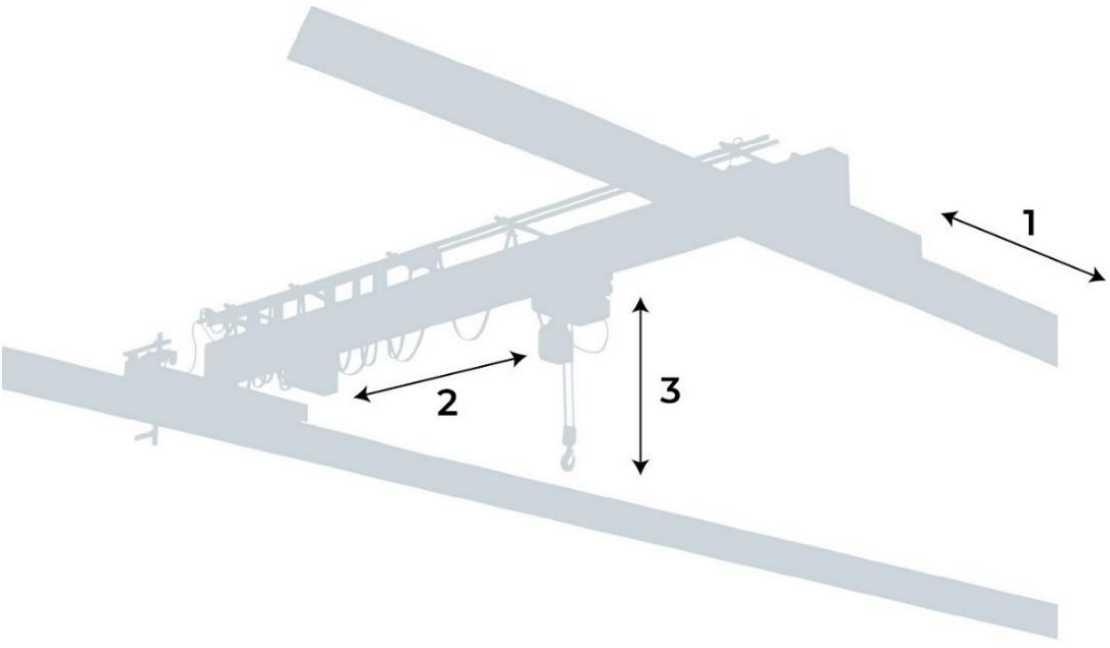

Figure 2. Axis of travel of Overhead cranes (Image source. R&M).

The various motions of the crane shown in

Figure 2 are explained as follows.

Axis 1: Long travel

Axis 1 depicts the travelling path of the bridge girder placed on the runway beams as shown in

Figure 2. The various parts of the overhead crane which is used to enable the movement of the crane is described in

Figure 3. Overhead Crane(Image credits: Konecranes).

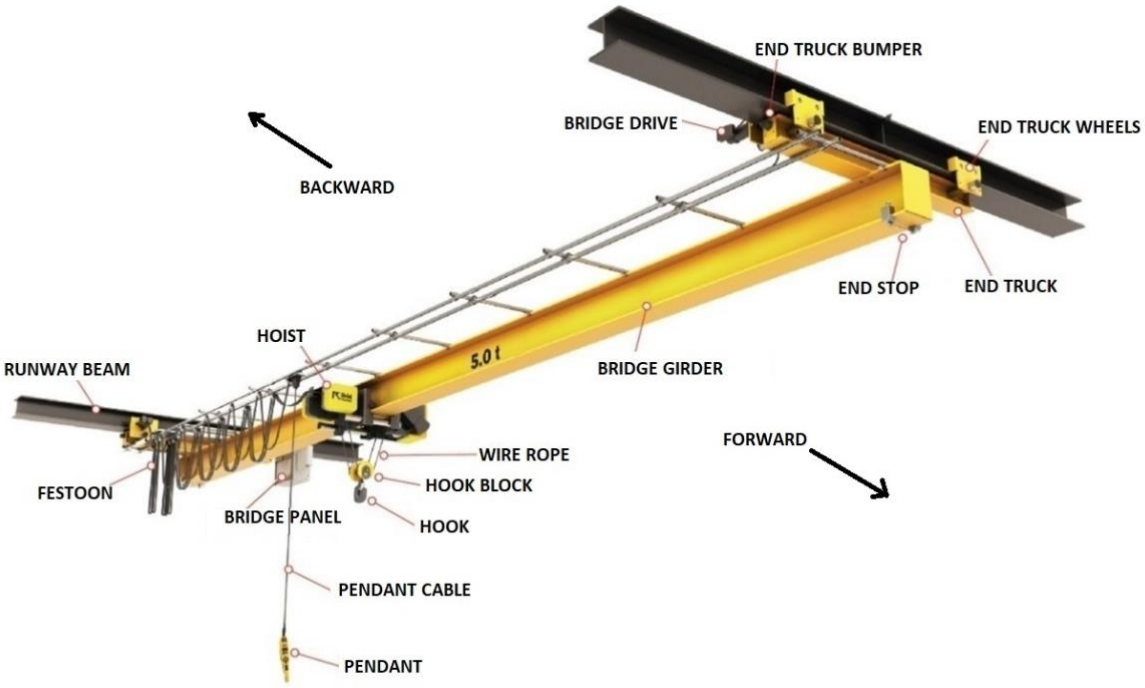

Figure 3. Overhead Crane(Image credits: Konecranes)

The bridge girder or the girder of the crane lies on two parallel runway beams. Based on the project requirements, the overhead crane can be a single girder crane or a double girder crane. The girder is fixed with wheels which help in the movement of the bridge over the parallel runways. The directions of the long travel motion are denoted by forward and backward motion of the bridge. The bridge is moved with the help of bridge drive. The bridge drive is electrified using conductor bar setup or cable festoons. The bridge should get constant power supply even at the extreme ends of the long travel motion. The bridge has end stop sensors which allows the PLC engineers to set the end points of long travel. The crane is fixed with buffers at both ends of the crane to absorb the impact in case of system

in case of system failure. In modern cranes the PLC is set in such a way that the travelling limits can be set right at the start.

Axis 2: Cross Travel

Cross travel is the travelling direction of the trolley on the bridge of the crane. The trolley is the mechanical object to move the hoist along the bridge girder of the overhead cranes. It facilitates the movement of the load connected to the hook in horizontal axis.

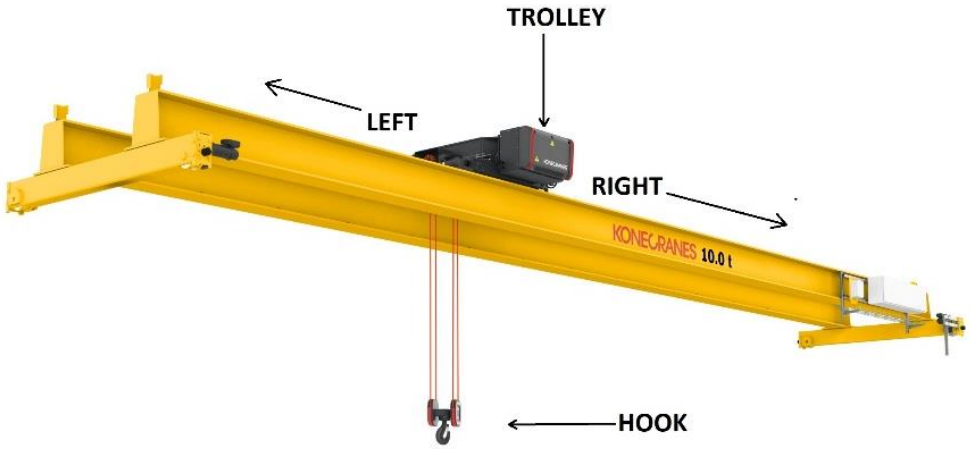

Figure 4. Cross Travel (Image Credits: Konecranes).

The type of trolley and lifting mechanism is dependent on the requirements of the project. Hence the electrification system of the trolley should be able to move along with the trolley. The trolley being a separate entity can be electrified using a separate festoon system also considered as the trolley festoon.

Axis 3: Hoist Up-Down movement

The load connected to the hook can be lifted or placed down using the hoist motors with this motion.

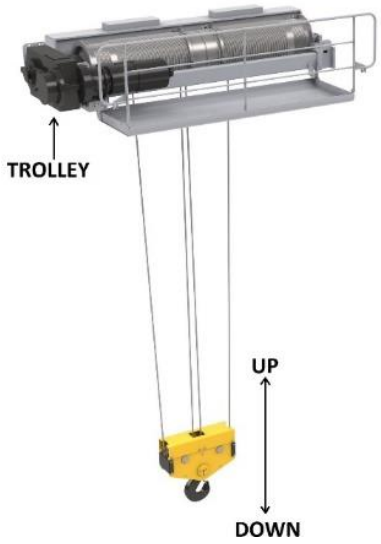

Figure 5. Hoist movements. (Image Credits: Konecranes).

The type of hook is dependent on the object to be lifted in the crane site. In certain projects multiple hoists are used which work in tandem to lift the heavy load.

2.2 Crane power supply system

Choosing an electrification system is one of the most important aspects in crane designing as various constraints need to be taken into consideration before reaching a conclusion. Conductor bar systems, cable festoons and cable reels are generally used for crane electrification system whereas for trolley electrification cable festoon systems can be used. Cranes used in mining, and nuclear power plants needs special attention when deciding the electrification system as the environment plays a vital role in the compatibility of the electrification system. Also, in factory environments there are certain design considerations depending on the object to be lifted.

Over the course of time different systems have been experimented to enable a safe and reliable electrification of cranes. With an aim for a more efficient and robust system there has been a gradual improvement in the electrifications process. These systems are chosen based on factors like cost, environment constraints, safety, and reliability.

The crane electrification systems currently used are listed below.

1. Conductor bars

Conductor bar system is used to enable the power transfer from a stationary source to a mobile device. The stationary part is aligned in a way that the moving part can be in proximity during the operation. A current collecting device is mounted on the moving part which is always in contact with the stationary conducting bars. The contact terminal facilitates the flow of electricity to the moving part of the crane.

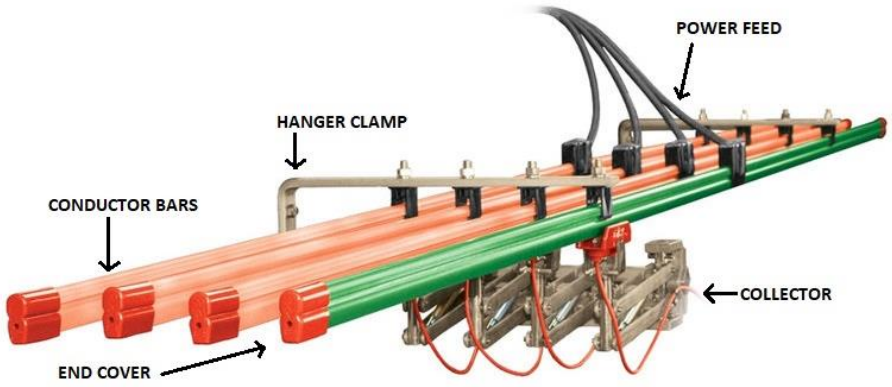

Figure 6. Conductor bar (Image Source: Conductix-Wampfler).

Conductor bars are cost-efficient electrification systems and one of the biggest advantages is the system can be easily upgraded in future. It was the most preferred choice for crane electrification in the past. A single conductor bar system can be used for electrification of multiple cranes in a single bay. Due to the design, it is one of the most suitable choices for low headroom sites.

2. Cable reels

Cables can be rolled up and stored when crane is in a standstill and can be retrieved when the crane is in motion. It is the preferred choice for cranes used in outdoor environments.

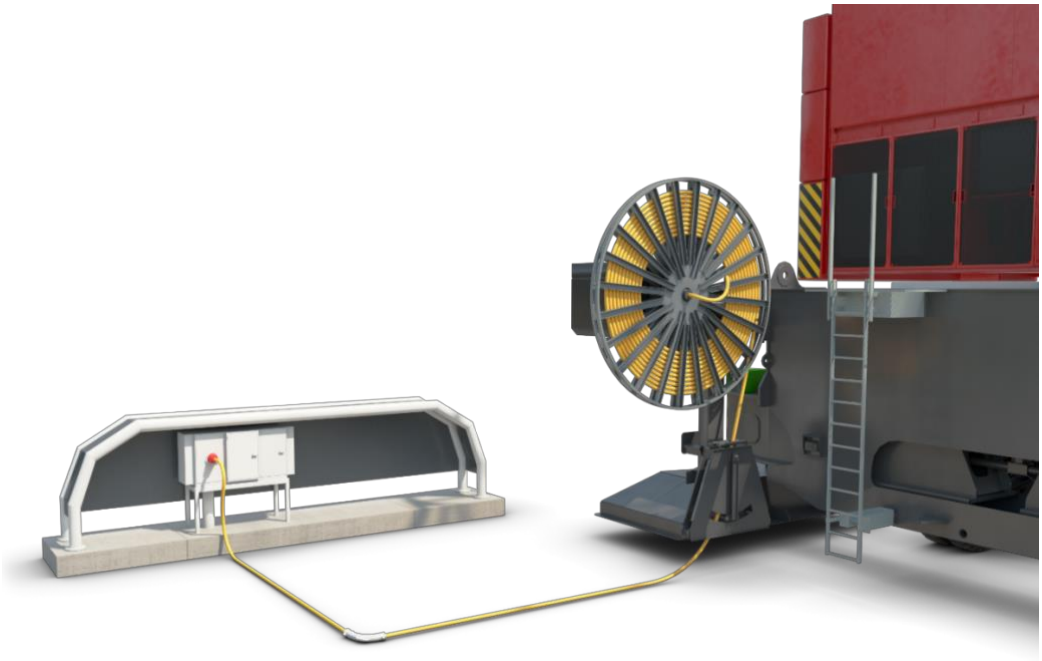

Figure 7. Cable reel setup (Image Source: Konecranes).

The above image shows a cable reel setup for a port crane connected to the power source. The design of the cable reel system is simple and does not need any additional hardware to operate it. The straightforward design of the cable reels is a good option for electrification for basic cranes. Due to a small number of hardware components and moving parts the need for service and maintenance is less. It is the one of the preferred choices for explosion proof applications.

2.3 EMC problems in Crane electrification system

Implementation of the advanced features needs various sensors, actuators, cameras of various kinds, transmitter-receiver modules, lasers, and displays which are integrated in the crane system(Atzori, Iera and Morabito, 2010). These sensors are connected using long cables which are susceptible to noise from the nearby drives or other EMI sources(Cacciato *et al.*, 1999). Although data can be transmitted using wireless data transmission techniques like WLAN, customers are not in favour of wireless communication due to the issues of network security(Nazir *et al.*, 2022).

The EMI caused due to 3-phase single core cables used in crane electrification impacts the signal reliability of data cables placed closed to them(Lo *et al.*, 2018).

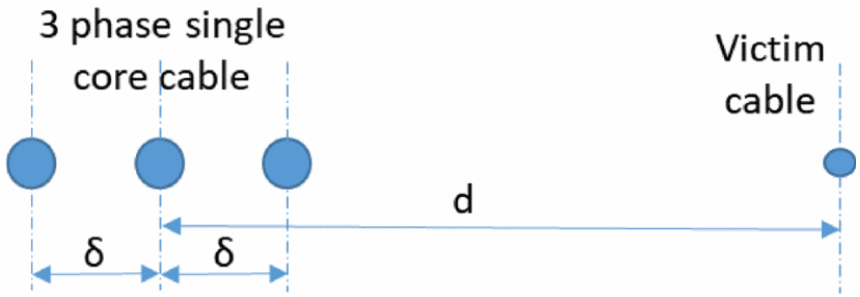

Figure 8. EMI issues(Lo et al.*, 2018)*

The electromagnetic compatibility is an important requirement to be considered by manufacturers to ensure that their product can withstand electromagnetic interferences. The most common sources of EMI in crane environment would be power lines, VFDs, and microprocessor-based equipment(Sarma and Sarma, 2013). Data transmission using UTP is impacted by EMI from power cables due to coupling mechanisms(Sarma and Sarma, 2013).

The Coupling of noise between a power supply cable and data cable may occur due to conductive coupling, capacitive and inductive coupling(Sarma and Sarma, 2013). In the case of cranes, the most common reason is capacitive coupling which arises when the power lines and signal cables are placed parallelly while cabling(Ismail, 2002). The effect of noise on the system is proportional. to the inverse of distance between power supply cables and data cables, length of the cable and strength and frequency of noise voltage(Martin, 1995).

Signal reliability is extremely crucial as issues in crane operation might lead to life threatening accidents. Hence an electrification system developed to overcome the EMI issues would be the best choice for modern cranes.

2.4 Limitations of the present electrification systems

Conductor bars has lots of advantages, but it was not the appropriate choice for the needs of modern cranes. In certain environments where there is a strict regulation for fire hazards and there is a need for an explosion proof system, the conductor bar setup cannot be used as there is a risk of spark (Martin, 1995). It is also not advisable to use conductor bar setup in chemical factories or humid environments increases the possibility of rusting which reduces the lifetime(Zhang et al., 2014). Data transmission is possible using conductor bar systems, but it is not a reliable system as there are chances of losing signal when the data collector is not in constant contact. There is a constant need for collector shoe replacement which increases the maintenance costs.

In cable reels the power cables and data cables run parallel to each other. This type of cable arrangement causes issues due to electromagnetic interferences(Liu *et al.*, 2022). Although optical fibre can be used for data transmission, it has always proven to be a costlier choice. Moreover, fibre optic cables are delicate as compared to copper cables and any damage can impact signal reliability(Cheng *et al.*, 2016). Cable reels is a suitable choice for gantry cranes but cannot be used for overhead cranes due to the type of crane movements.

In recent years conductor bar system and cable reels have been upgraded to satisfy modern day needs but they are not suitable in certain scenarios like harsh environments, outdoor cranes and in cranes using lots of signal cables for data transfer

Hence there is a need for an electrification system which is developed to solve the issues of data cables. The aim of the engineers is always on developing a solution for the electrification of the diverse types of cranes by considering factors like safety, reliability, longevity, and cost.

3 Cable festoon system

Cable festoon systems are used for the electrification of cranes and trolleys using long power cables. It is usually used on overhead cranes, port cranes and material handling cranes. The festoon cables can be also used to connect the pendant of the crane.

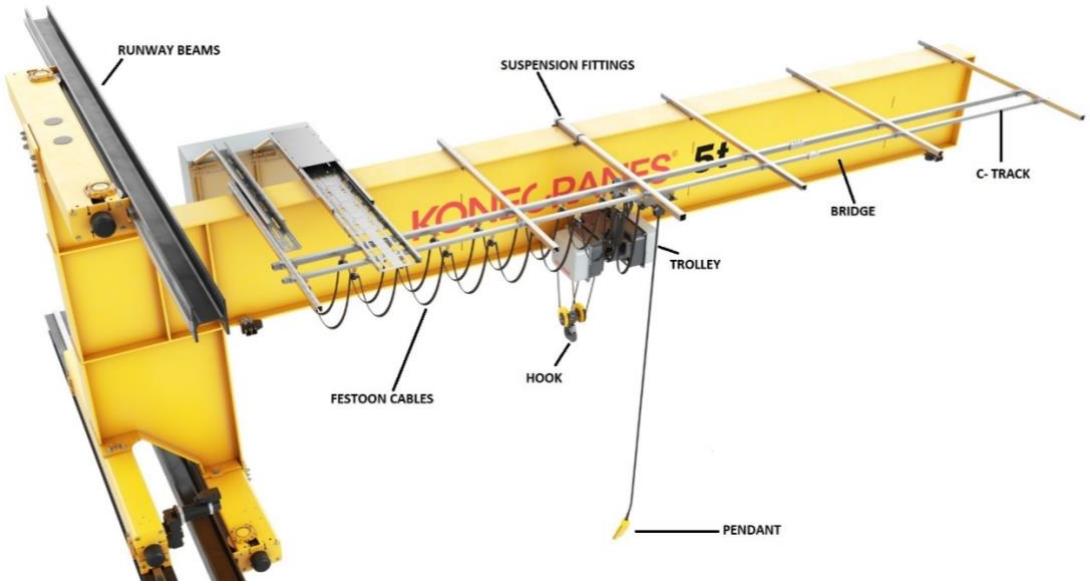

Figure 9. Cable festoon system (Image credits: Konecranes).

A cable festoon system comprises of an I-beam or a C-track which is fixed parallel to the girder as shown in Figure 9. It mainly comprises of cable trolleys that can slide on the I-beam or inside the C-track rail with the help of wheel attached to the trolleys. One end of the track or the rail contains the fixed trolley whereas the other end is equipped with a towing trolley. A taker arm is used to drag the towing trolley from start point to the end point. The cables are then placed on the saddles of the cable trolleys by forming loops as shown in Figure 9. As the towing trolley moves along the track with the help of taker arm, it drags all the other cable trolleys. This enables the cables to reach the desired position.

Pendant is the controller of the crane. Pendant can be connected using a separate light weight cable festoon system.

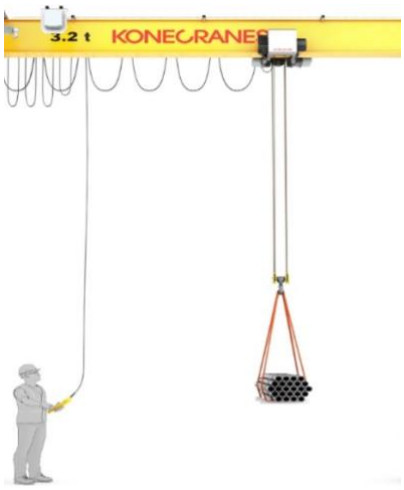

Figure 10. Pendant (Image credits: Konecranes).

Pendant can be dragged in any direction by the crane operator depending on the length of festoon cable. In modern cranes pendants are replaced by remote control devices.

The detailed working of the cable festoon along with the components to configure the festoons are mentioned in section 3.2

3.1 Advantages and limitations of Cable Festoon system

The cable festoon systems comprise of fewer parts as compared to the other electrification systems which reduces system complexity and makes is simpler to operate. The design makes it a suitable choice for crane and trolley electrification. Due to the use of hard-wired cables in cable festoon systems are the preferred choice for explosion proof environments and extreme conditions like chemical factories and humid environments.

A wide range of cable festoon systems are available in the market, but the company decided to develop their own festoon system with added benefits and design advantages. The advantages of KBK festoon system over commercially available festoon systems are listed as follows.

1. I-beam vs C-track system

   The commercially available systems use an I-beam system where as the KBK system comprises of a C-track.

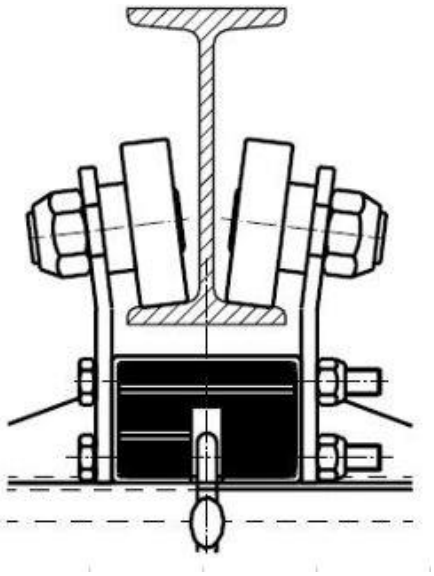

Figure 11. I beam with cable trolley.

The following are the issues in the I-beam system based on issues faced in previous customer projects:

- The cable trolleys used in I-beam festoon comprises of bearings which increases the need for periodic maintenance.
- In case of lack of maintenance, the cable trolley can be stuck during operation.
- The movement of trolleys is not smooth as compared to C-track festoon system.
- There is also an increased risk of cable trolley derailing from the beam.
- As the cable trolleys are exposed to the surrounding environment, the life span of cable trolleys used in I-beam cable festoon system is comparatively less.
- The cable trolleys are also fitted with a tension rope to pull the trolleys during operation.

All the above issues can be avoided using the KBK festoon system using the C-track rails due to design advantages.

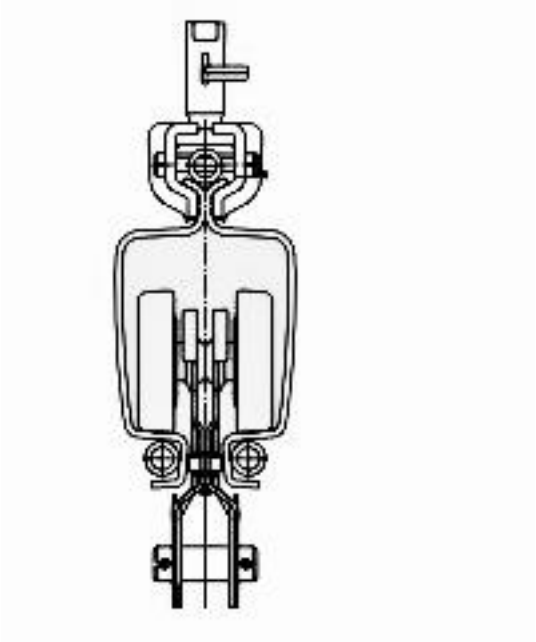

Figure 12. C- track festoon with cable trolley.

Since the trolleys are covered and well protected inside the C-track the cable trolleys are well protected. Also due to the proper covering there is less wobbling of cable trolleys during movement as compared to trolley used with I- beam.

2. Weight and Size

   The I-beam setup increases the weight of the total festoon system. Compared to the I-beam, the KBK system is considered as a lightweight festoon system. On crane sites where there are space constraints, KBK festoon proves to be the best option due to its smaller package.

3. Economic profits

   Using an in-house product is always lucrative when compared to procuring products from a different manufacturer. Supply chain issues would be solved as well as the company would be aware of the demands well in advance. The cost of transportation is also well reduced as the components are manufactured close to the place of assembly of the crane.

4. Curved track

   KBK festoon also has the benefit of using a curved track which is not possible in the phase of I-beam festoons as well as other electrification system.

Figure 13. Curved track.

This gives the advantage and flexibility to use the KBK festoon system at all possible scenarios.

5. Separate Data cable trolley attachment

Various methods can be used to reduce the impact of electromagnetic interferences but when it comes to industrial applications the cost plays a key role in deciding the solution.

The two prominent ways to reduce the impact of electromagnetic interference(Lock, 2012) would be:

- Physical separation
- Use of shielded cables

The KBK festoon cable trolleys are designed to connect an additional cable trolley attachment to accommodate the data cables separately. The design uses the principle of physical separation of cables to prevent issues due to electromagnetic interference.

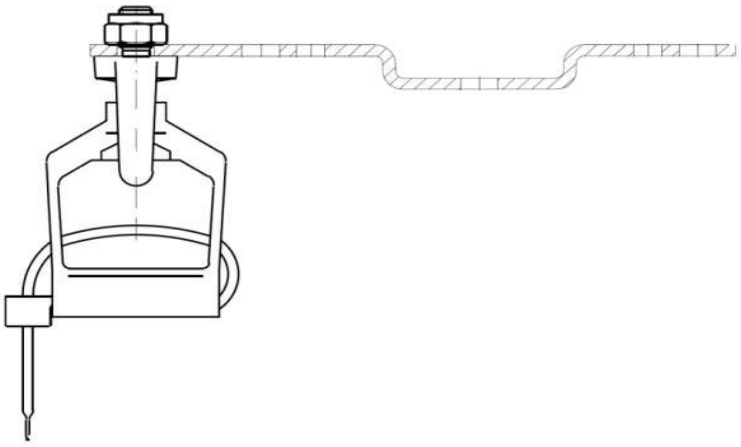

Figure 14. Cable bracket (Image credits: Konecranes). (Lock, 2012).

The cable bracket attachment would contain only the data cables and it would be at a specific distance from cable trolley containing the power supply cables.

Figure 15. Cable festoon with Data cables attachment (Image credits: Conductix wampfler).

The above image illustrates a heavy-duty festoon system by Conductix Wampfler which can add a cable data saddle exactly below the power cable saddle. But when the cables are gathered on one end of the track, there is still a possibility of cables getting closer to each other.

To overcome this issue the KBK festoon system allows the user to attach the cable saddles to the side of the power cables. The cable bracket attachment can be attached on either side of the trolley or in the middle.

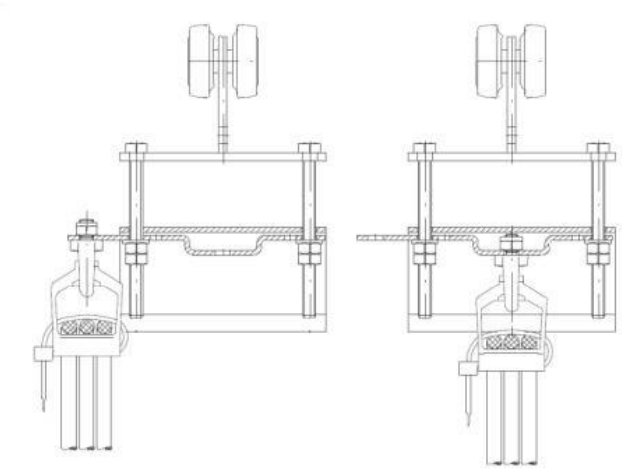

Figure 16. Cable bracket position (Image credits: Konecranes).

Moreover, cable brackets can be used to avoid excessive movement of data cables and to maintain the distance between signal and power cables.

If the data cable saddle is attached the weight of the data cable saddle and the signal cables should be taken into consideration while calculating the weight distribution for maintaining the balance.

KBK festoon system is a lightweight system which has its limitations as well. The KBK festoon system is not the suitable choice if the cable package weight is higher than the weight limits. For heavy weight system, I-beam festoon should be preferred as compared to the KBK festoon systems. The other limitation of KBK festoon system is the slow speed of operation. Although the operation is smoother as compared to I-beam festoons but due to the absence of towing cable the speed of operation is slower.

3.2 Working of Cable Festoon System

The cable trolleys used in the system is a very crucial part of the cable festoon system. Figure 17 below illustrates the C-track with cable trolleys and a detailed picture of the cable trolley saddle.

Figure 17. Cable trolley setup (Image credits: Demag).

A cable trolley is made up of cable saddle and a wheel assembly to glide through the track. The cables used for electrifications can be placed on top of the cable trolley saddles. Flat cables as well as rounded cables can be placed on top of the cable saddle. The designer must ensure the weight of the cable package is distributed evenly in equilibrium to maintain stability of the festoon system. If the weight is not distributed evenly, the cable trolley can swing on one side during operation which may reduce the stability of the festoon system.

End clamp is used to hold the cable. It can also be considered as the fixed cable trolley or the starting point of the festoon systems.

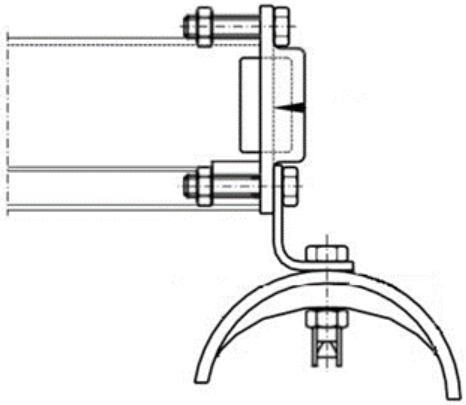

Figure 18. End clamp (Image credits: Konecranes).

Towing trolley is connected to the taker arm to move the cable trolleys connected to the track or the I-beam. As the taker arm moves, it drags the towing trolley along the rails/beam which further pulls all the other cable saddle trolleys.

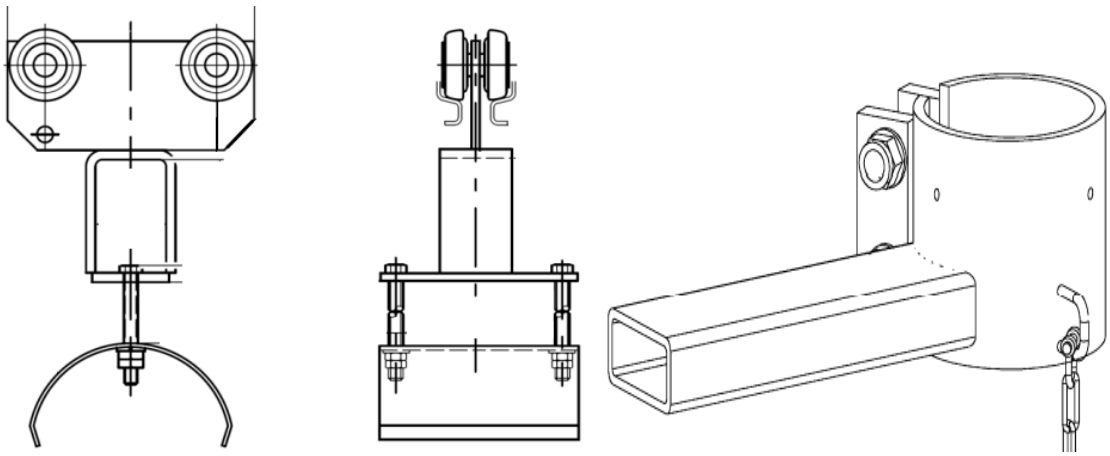

Figure 19. Towing trolley and taker arm (Image credits: Konecranes).

Depending on the design of the main trolley, taker arms can be replaced by direct coupling of towing trolley with the bridge trolley.

3.3 Festoon parameters and calculation techniques

A cable festoon system comprising of C-track and the trolleys are manufactured by Konecranes and later given the name ‘KBK festoon system’. After designing the C- track, cable trolleys and the additional components there was a need for the development of a calculation tool for this festoon system. The tool would help the designer by displaying a warning message when the parameter value is not in the scope of safety limits.

The methodology used in developing the calculation tools are as follows:

Step 1: Study the Crane and festoon structure.

The crane layout was first studied in detail to understand the crane terminologies and understand the different design parameters of the crane.

Step 2: Figure out the parameters to be taken into consideration for festoon calculations.

The crane layout gives the dimensions of various crane parameters. Among these, the essential parameters were selected to design the crane festoon system.

Step 3: Research on possible design constraints.

While designing the cable festoon system, all possible constraints were taken into consideration.

For e.g., if the cable loop height is kept long then it can touch the lifted load.

Step 4: Consider the product constraints and customer requirements in the tool

Along with the design constrains, it is also mandatory to consider the manufacturer guidelines to ensure safety and stability of the festoon system.

Step 5: Develop the formula.

The logic behind the formula was decided based on the shape the loops formed on the festoon system and were later modified depending on the dimensions of the components.

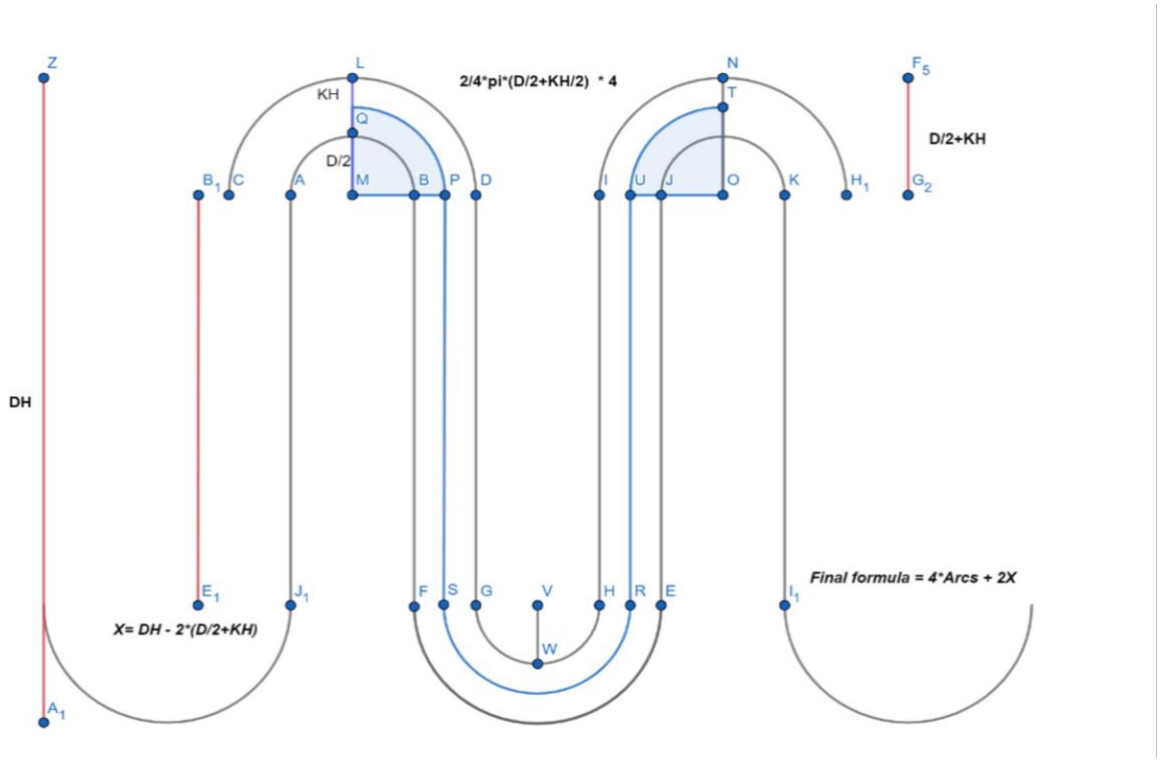

Figure 20. Formula Testing

The formulas were then used on distinct types of festoon system already in use to verify the logic behind the formulas. Once the logic was determined it was then simplified to use fewer parameters for the ease of use of the designer.

Note: The dimensions of the components of festoon system have not been mentioned in the equations mentioned in the thesis.

Step 6: Use iterative calculation to find the optimum parameters.

The design parameters are dependent on each other, hence modifying a single parameter value has an impact on all the other design parameters.

The impact of parameters on each other while designing the cable festoon system has been explained with the help of a flowchart mentioned below,

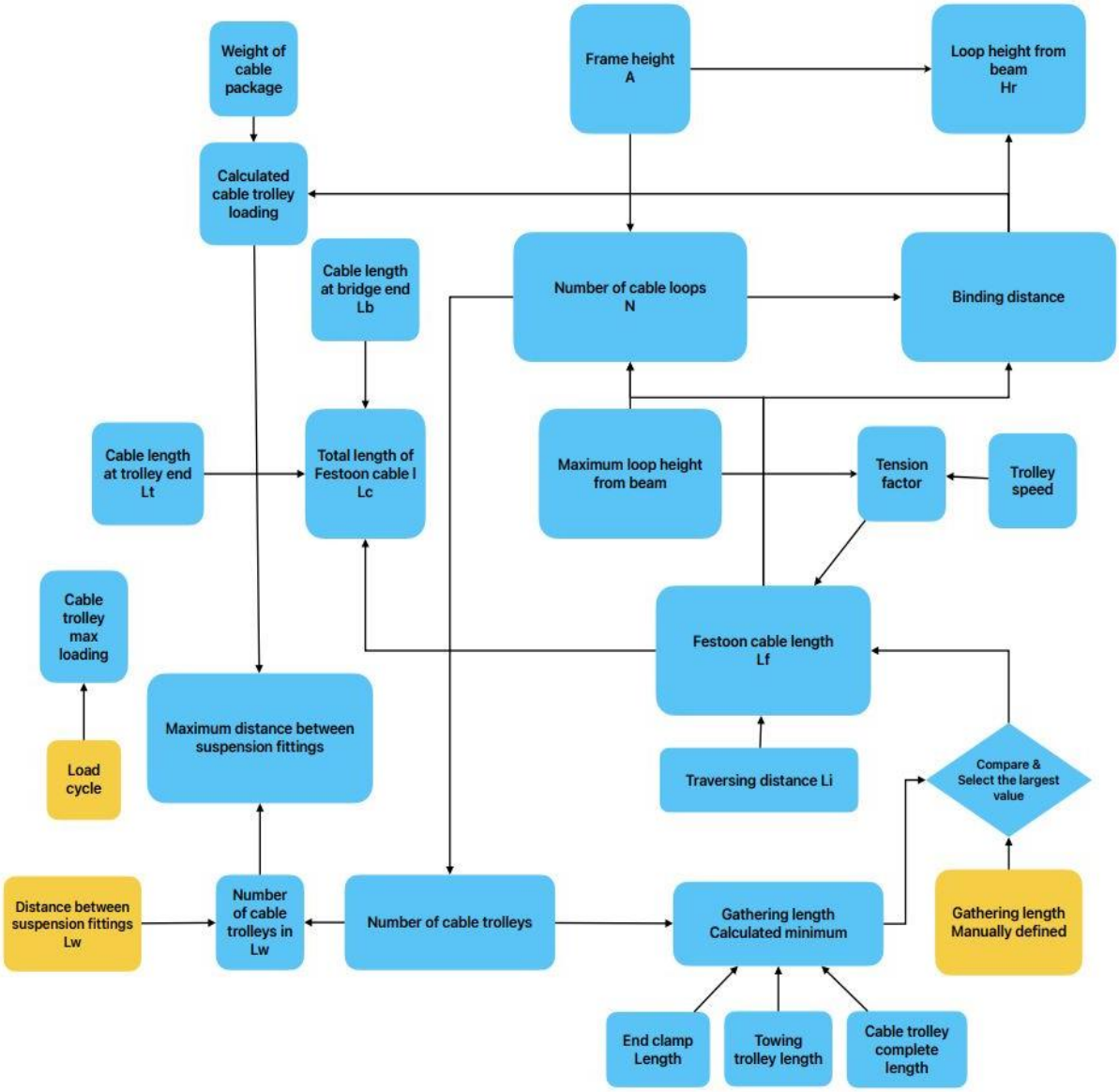

Figure 21. Flowchart of parameter interdependency.

The calculations are done using Microsoft Excel to take advantage of the Iterative calculation feature needed for current task.

The aim is to find the best possible solution which can satisfy all the parameter constraints. In Iterative calculations, the parameters are connected using circular references. The function iterates itself till a solution is obtained.

OUTPUT DATA		
Number of cable loops N	9	Loops
Binding distance Ls	4001,56	mm
Loop height from beam Hr	1960,78	mm
Number of cable trolleys N	8	Trolleys
Gathering Length (calcualted minimum)	2050,0	mm
Gathering Length (manually defined)	2740	mm
Tension Factor P	1,1	
Festoon Cable Length Lf	36014	mm
Total length of cable Lc	74014	mm

Figure 22. Circular Reference in Microsoft Excel

Parameters are tuned till there are no warnings and all the conditions are satisfied. After satisfying the conditions of all parameters, the designer then tries to fine tune the values to get a better design and try to reduce the number of components needed.

The list of parameters can be divided into three sections. Electrical, Mechanical and Output Parameters.

3.3.1 Electrical Parameters

The electrical parameters used in the tool as listed as follows:

1. Cable package height – The combined thickness of all the cables is used to calculate the cable package height(st). It is used to decide the suitable cable trolley.

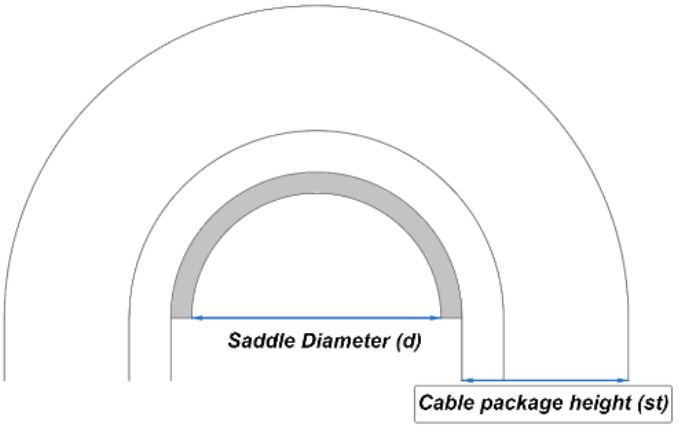

Figure 23. Cable Package height

The cable which the highest thickness amongst all has the biggest bending radius, so it must be placed on top of the other cables with a relatively smaller bending radius. This would prevent the damage to the cable due to excessive bending. The designer must also ensure that the cable package height is less than the maximum available space at the cable trolley saddle. Failure to do so will display a warning message in the calculation tool.

2. Cable package width – The total width of the cable package is measured to select an appropriate cable trolley of suitable saddle width. The width of cable package should not be greater than the cable saddle width.

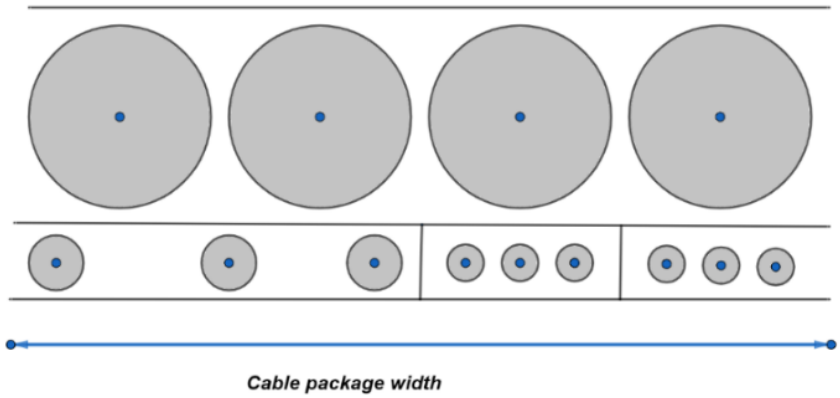

Figure 24. Cable package width.

The weight must be balanced on both the sides to maintain the centre of gravity to improve trolley stability while the festoons are in motion. Failure to maintain the balance would result trolleys aligning to one side due to the weight of the cable package.

The cable package width is necessary to select the appropriate cable saddle to accommodate the cable package.

3. Cable trolley complete length ($L_{CT\ MAX}$) – The minimum length of the cable trolley required so that the wires do not collide while gathering. Collision of cables may result in damage and reduce the lifetime.

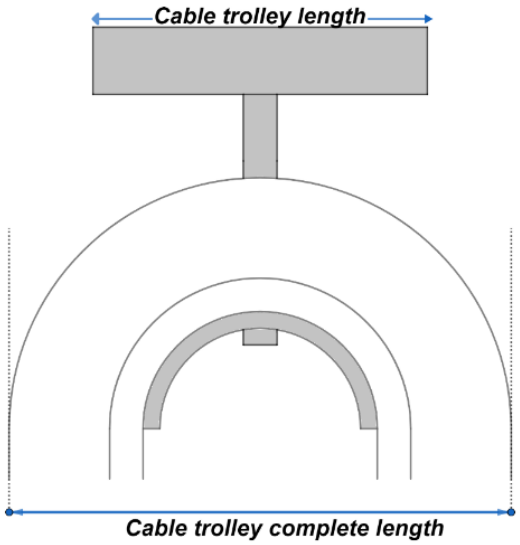

Figure 25. Cable trolley

$$L_{CT\ MAX} = 2 * (R_{CT} + S_T) \quad (1)$$

Where R_{CT} is the radius of the cable trolley used and S_T is the height of the cable package.

After placing the cables on the cable saddle, the cable trolley minimum length should not be greater than the length of the cable trolley.

In light weight applications the damage due to cable collision is negligible. Cable trolley complete length should be considered rather than cable trolley length during the calculation of other parameters. This length has been taken into consideration as the cable trolley length can be smaller than the cable trolley complete length based on the cable package height.

4. Towing trolley length – Towing trolley is used to drag the rest of the cable trolleys in the cable festoon systems. The towing trolley length would be used in calculating the cable length and the trolley can be selected based on the application.

5. End clamp length- The length of the end clamp assembly is taken into consideration as end clamp is considered as the starting point of the cable festoon system.

3.3.2 Mechanical Parameters

The Mechanical team decides the mechanical parameters. These parameters are based on customer requests, crane site constraints as well as inputs from the structural engineer. The mechanical parameters used in the tool are listed as follows:

1. Gathering Length - Gathering length also known as the Hook approach is the total length when all the cable trolleys are collected in the beam at one end. In some cases, the Hook approach parameter can be suggested by the customer based on the requirements. The minimum gathering length will also be calculated based on the number of cable trolleys.

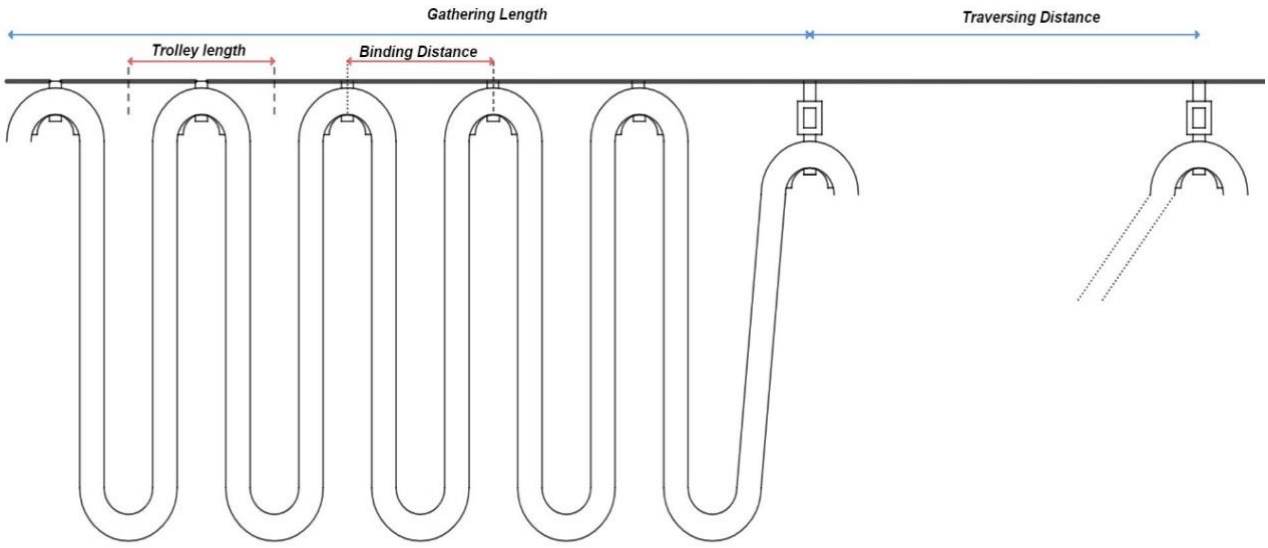

Figure 26. Gathering Length.

2. Minimum Gathering length($L_{G\,MIN}$)

$$L_{G\,MIN} = L_{TT} + (L_{CT} * N_{CT}) + L_{ET} + 150 \quad (2)$$

where L_{TT} is the length of towing trolley, L_{CT} is the Length of cable trolley, N_{CT} is the number of cable trolleys and L_{ET} is the length of end trolley.

Note: The additional 150mm is added as buffer value for safety reasons.

The manually defined gathering length should be more than the minimum gathering length. A bigger gathering length implies a smaller traversing distance which thereby restricts the hook movement beyond a certain point.

3. Traversing Distance- Traversing distance can be calculated by subtracting the hook approaches on both ends from the total span of the crane

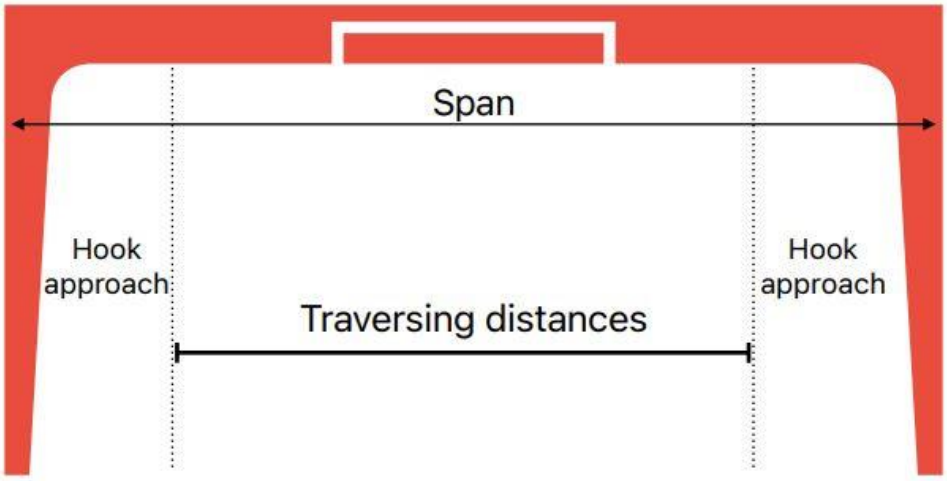

Figure 27. Traversing distance.

This parameter helps the designer understand the travelling area of the hook. This parameter is very crucial as it decides the working of the crane.

4. Towing trolley speed– The speed at which the crane trolley moves is used to calculate the tension factor.

5. Cable Tension factor (*P*) – The table is provided by the structural engineering team. The value is obtained by traversing the cable tension matrix provided by the manufacturer with two parameters for traversal being maximum loop height from beam and crane travelling speed.

Table 1: Cable tension factor

Cable tension factor, P					
	Maximum loop height from beam(m)				
v (m/min)	0	0,8	1,2	2	3,2
0	1,1	1,1	1,1	1,1	1,1
33	1,15	1,1	1,1	1,1	1,1
41	1,2	1,15	1,1	1,1	1,1
51	1,25	1,2	1,15	1,1	1,1
64		1,25	1,2	1,15	1,1
81			1,25	1,2	1,15
101				1,25	1,2

6. Cable length at building end (*Lbu*) – In certain environments like waste to energy plant or nuclear power plants the electrical cabinet might be placed at a different place in the building and not on the crane. At such instances, the cable length from the building to the crane should be taken into consideration. This parameter is only applicable during the calculation of crane festoon.

7. Cable length at Bridge end (*Lb*)- The length of the cable on the bridge to the crane cubicle which is placed on the bridge itself.

8. Binding distance (*Ls*) – The distance between the midpoint of two cable trolleys.

$$Binding\ Distance\ (Ls) = \frac{L_F}{N} \qquad (3)$$

Where L_F is the Length of the festoon cable and N is the Number of cable loops.

9. Loop height - The three main parameters concerned to loop heights are explained in the figure below.

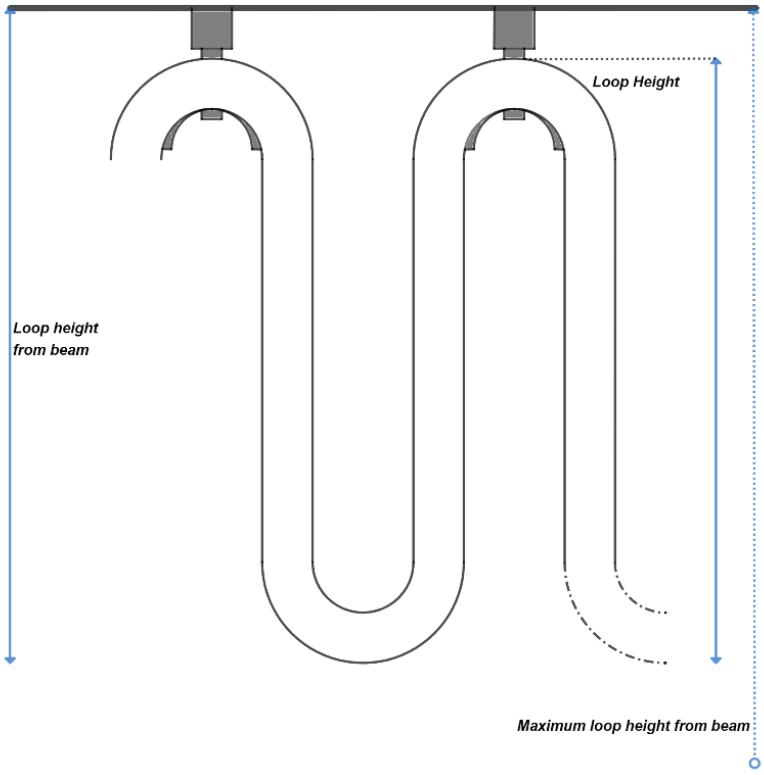

Figure 28. Different loop height parameters.

a) Loop height from the beam(H_r): It is the measure of to the loop height from beam to the bottom of the cable loop.

b) Loop height: Distance from the top to bottom of the cable loop.

c) Maximum loop height from the beam: It is the value of the maximum allowable loop height from the beam.

Maximum loop height from beam is decided based on the crane site. It is the measure of how low a cable loop can hang from the beam without causing an obstruction to the lifted load. The height of the cable loops has a significant impact on the number of cable trolleys used in the cable festoon system.

10. Straight Section rails – The KBK trolleys are installed on C-track straight sections of variable lengths. The number of straight sections depends on the length of the cable festoon system.

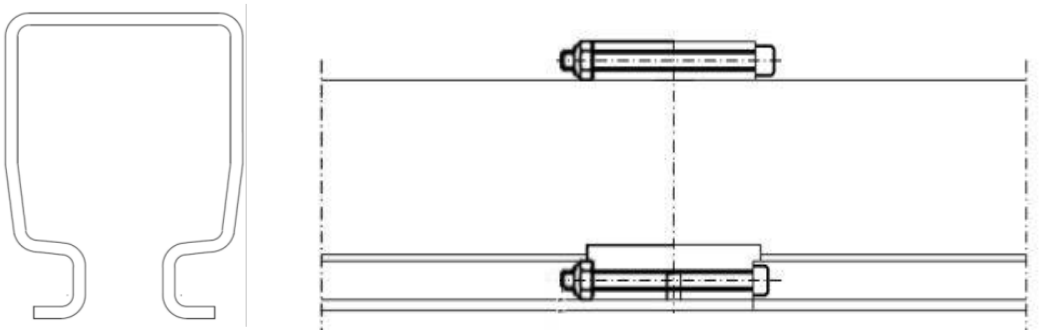

Figure 29. C track straight section with joint bolt set (Image credits: Konecranes).

The straight sections are connected using joint bolt sets. The entire track assembly is attached to the system using suspension fittings.

11. Load per cable trolley – The maximum weight of the cable an individual cable trolley can withstand is calculated to avoid the stress on the straight sections and suspension fittings.

$$\text{Load per cable trolley } (W_{CT}) = \frac{(L_{G\,DEF} + L_I) * P * W_C}{N_{CT} + 1} \quad (4)$$

Where $L_{G\,DEF}$ is Defined Gathering length , L_I is traversing distance, P is tension factor, W_C is Weight of cable package and N_{CT} is number of cable trolley.

Based on the calculated permissible weight and manufacturer guidelines the suitable cable trolley loading can be verified.

12. Load cycle- Load cycle can be defined as the continuous and repeated process involved in moving a load. This value is used to determine the maximum load that can be carried based on the stress the load puts on the crane. This value is obtained by the product development team after structural analysis.

Table 2. Load cycles.

Cycles	Maximum loading (kg)
8000	100
16000	100
32000	100
63000	100
125000	80
250000	56
500000	36
1000000	24

Note: Since the product is in development phase the accurate values of load cycles are not available and hence an estimated data based on a similar festoon system has been taken into consideration for the purpose of calculation in this thesis.

13. Number of cable trolleys in section

$$L_W\ (N_{CT}L_W) = \frac{L_W}{L_{CT\ MAX}} \tag{4}$$

Where L_W is Distance between suspension fittings, $L_{CT\ MAX}$ is Cable trolley complete length.

The number of cable trolleys in a particular section can be calculated using the above formula and the guidelines from the manufacturer for maximum distance between suspensions based on the structural integrity of the system is mentioned below.

When the cables are gathered the entire weight of the cable trolley in a particular section should be supported by the suspension fittings holding the beams. Failure to calculate

the weight accurately might lead excess stress on the suspension fitting which might lead to brakeage.

14. Maximum distance between suspension fittings ($L_{W\,MAX}$): Load per cable trolley and number of cable trolleys in section L_W is calculated and these values are used to traverse the table to calculate the maximum distance between two suspension fittings.

Table 3: Suspension distance

Maximum distance between suspensions for KBKfestoon system													
Number of cable trolleys in section Lw	KBK festoon system												
	Steel Cable trolleys							Heavy Duty Cable trolleys					
	Load per cable trolley (kg)												
	10	15	20	25	30	35	40	50	60	70	80	90	100
	Maximum distance between suspensions (m)												
1	5	5	5	5	5	5	4,8	4,3	3,9	3,6	3,4	3,2	3
2	5	5	4,8	4,3	3,9	3,6	3,4	3	2,8	2,6	2,4	2,3	2,1
3	5	4,5	3,9	3,5	3,2	2,9	2,8	2,5	2,3	2,1	2	1,8	1,7
4	4,7	3,9	3,4	3	2,8	2,6	2,4	2,1	2	1,8	1,7	1,6	1,5
5	4,3	3,5	3	2,7	2,5	2,3	2,1	1,9	1,7	1,6	1,5	X	X
6	3,9	3,2	2,8	2,5	2,2	2,1	1,9	1,7	1,6	1,5	X	X	X
7	3,6	3	2,6	2,3	2,1	1,9	1,8	1,6	1,5	X	X	X	X
8	3,4	2,8	2,4	2,1	2	1,8	1,7	1,5	X	X	X	X	X
9	3,2	2,6	2,2	2	1,8	1,7	1,6	X	X	X	X	X	X
10	2,5	2,5	2,1	1,9	1,7	1,6	1,5	X	X	X	X	X	X

The data was obtained from the structural analysis of the KBK festoon systems.

3.3.3 Output Parameters

The output parameters are used to decide the optimum number of components needed as well as the design of the cable festoon system. Deciding the most appropriate value whilst considering all the trade-offs is one of the aims of these calculations.

1. Number of Cable loops (N) – The cables which will be placed on the cable trolleys will form N number of loops and based on the loop calculations the number of cable trolleys can be determined.

$$\text{Number of cable loops } (N) = \frac{Lf}{2*(LH_{max}-A)} \quad (5)$$

Where L_f is festoon cable length, LH_{max} is maximum loop height from beam, A is Frame height.

2. Number of cable trolleys (N_{CT}) - The number of cable trolleys needed can be easily calculated using the formula.

$$\text{Number of cable trolleys } (N_{CT}) = N - 1 \quad (6)$$

Where N is the number of cable loops.

3. Festoon cable length (Lf) -The length of the cable that covers the length of gathering distance and travelling distance comprises of festoon cable length.

In the calculation of L_F the minimum gathering length $L_{G\,MIN}$ and the manually defined Gathering length $L_{G\,DEF}$ are compared if $L_{G\,DEF} > L_{G\,MIN}$; $L_{G\,DEF}$ is taken into consideration.

$$\text{Festoon cable length } (L_F) = P * (L_i + L_{G\,DEF}) \quad (7)$$

Where P is tension factor, L_i is traversing distance and $L_{G\,DEF}$ is defined gathering length.

4. Total length of Cable (Lc) – The addition of all the cable lengths at different ends gives the total cable festoon length.
For crane festoon:

$$\text{Total length of cable } (L_C) = L_{BU} + L_B + L_F \quad (8)$$

Where L_{BU} is cable length at building end, L_B is cable length at bridge end and L_F is festoon cable length.

For trolley festoon:

$$\text{Total length of cable } (L_C) = L_B + L_F + L \quad (9)$$

Where L_B is cable length at bridge end and L_F is festoon cable length and L_T is towing side length.

5. Distance between suspension fittings *(Lw)* – The straight section connected using track joint bolts needs suspension fittings at a particular interval to hold the weight of the track and cables.

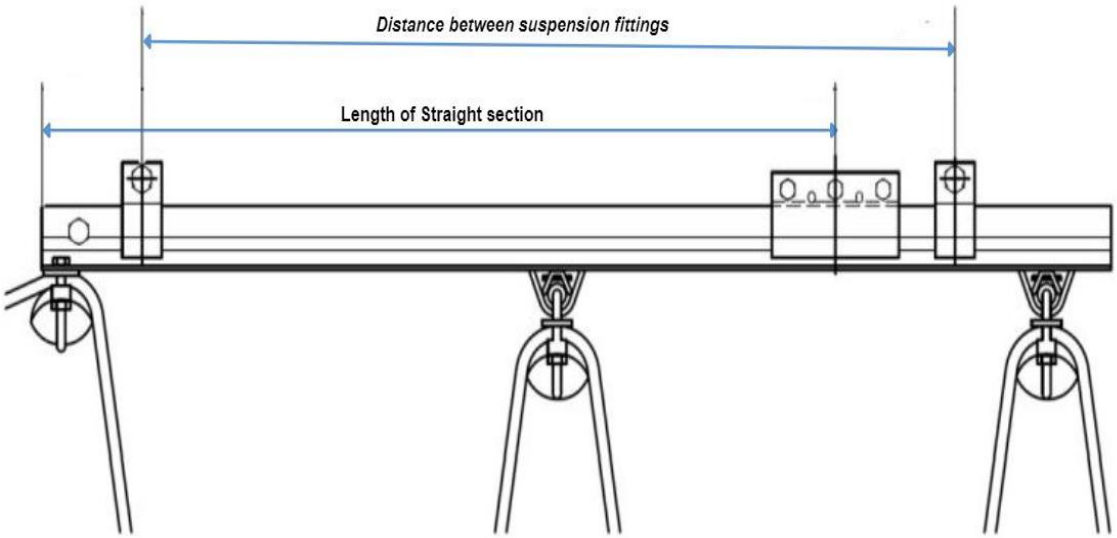

Figure 30. Suspension fittings for straight section (Image credits: Konecranes).

When the cable trolleys are gathered, the number of cable trolleys in that section along with the cable weight should be sustained by the suspension and the beam. The suspension fitting distance should be calculated carefully to avoid the collapse of festoon system due to overweight. Based on the number of cable trolleys at a particular section the length of L_W can be adjusted to find the optimum distance between suspensions. Too many suspension fittings would also result in a waste of money so finding the optimum number of suspensions needed would be the goal. To finalise distance between suspensions number of cable trolleys at a particular section, the load per cable trolley and the maximum distance between suspensions are taken into considerations.

The calculation starts with a random value of L_W to begin the iterative calculations and then adjusted to get close to the maximum possible distance without structural failure.

4 Results

To test the working of the tool an older customer project has been selected and a crane festoon would be designed for that crane dimensions. Due to circular referencing of parameters in Microsoft Excel, the functions iterate till the solution is obtained.

4.1 Tool implementation

Once the deal with the customer has been finalised the Mechanical Design team prepares a General Arrangement drawing based on the crane type, crane dimensions, and the crane site dimensions. Figure 31 shows a small section of the GA drawing which gives the designer a clear understanding of the crane type and crane dimensions.

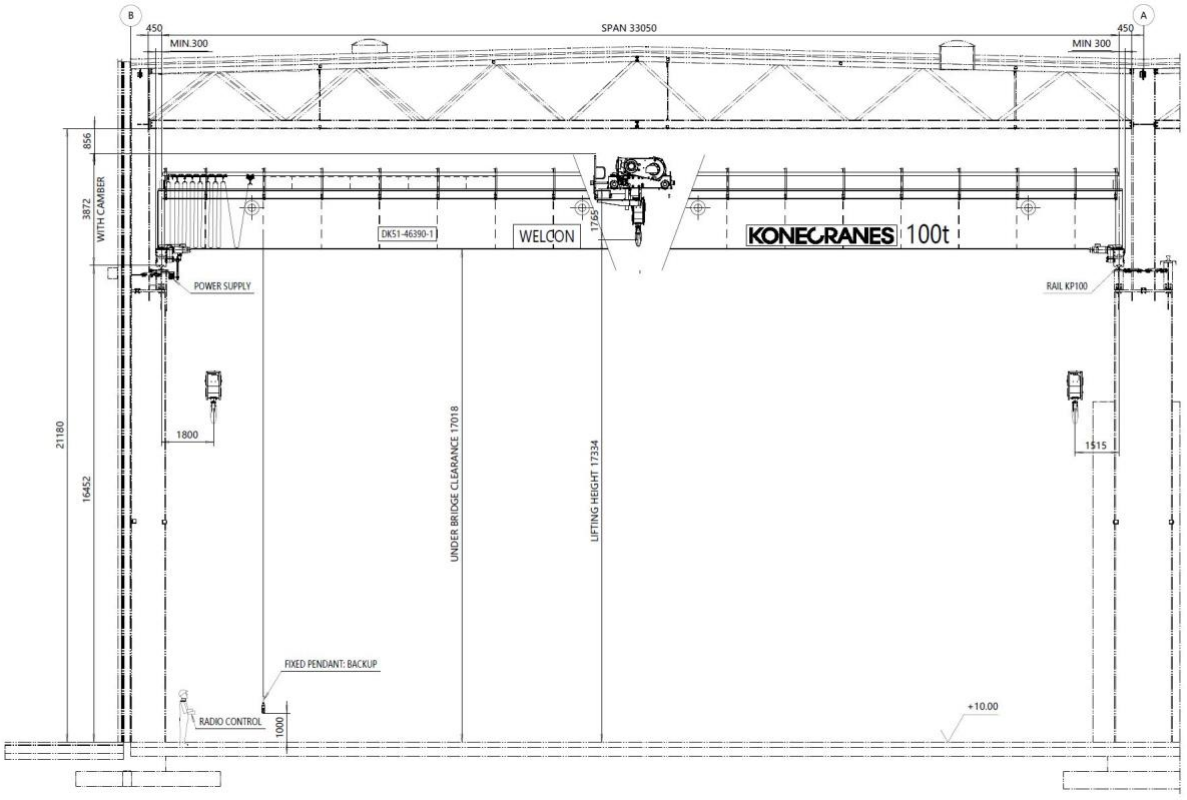

Figure 31. General Arrangement (GA) drawing (Image credits: Konecranes).

Figure 32 is a part of the GA drawing which shows a plan view of the bridge and trolley layout which will be useful while designing the trolley festoon system. GA drawing helps the designer understand the type of trolley, its dimensions and placement of the cabinet.

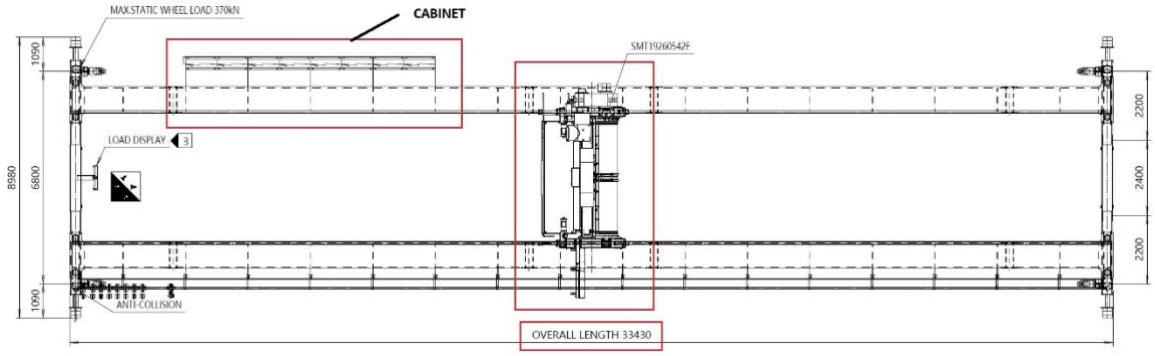

Figure 32. GA drawing (Bridge) (Image credits: Konecranes).

Based on the customer process and customer requirements, a hook approach is decided. The other important parameters suggested based on the crane site and crane design are the mechanical parameters like traversing distance, trolley speed, cable length at bridge end and cable length at trolley end.

After receiving the parameters from the mechanical team, it is now the job of the Electrical Engineer to start designing the festoon system. The electrical engineer also has access to the GA drawing to get details on other parameters for festoon calculations.

An individual festoon system is designed for the crane as well as the trolley of the crane. The procedure to calculate the parameters of the festoon is same for trolleys and cranes. Hence the procedure for calculating the trolley festoon will be described in detail. A customer project will be taken as an example to demonstrate the working of the tool.

The following parameters were obtained by the mechanical design team which will be used for the calculation purpose. These parameters are based on customer request and design guidelines.

Table 4 Mechanical Parameters

Parameters	Value	Units
Maximum loop height from beam	2080	mm
Gathering length	2740	mm
Traversing distance	30000	mm
Trolley speed	20	m/min
Cable length at bridge end	27000	mm
Cable length at trolley end	11000	mm
Type of track	KBK	-

The designer then decides the cable package placement to maintain the balance on the saddle of the cable trolley. A separate calculation tool is used to calculate the best possible cable arrangement for obtain proper weight distribution on cable saddle. The Figure 33 shows the efficient places of cables to avoid imbalance.

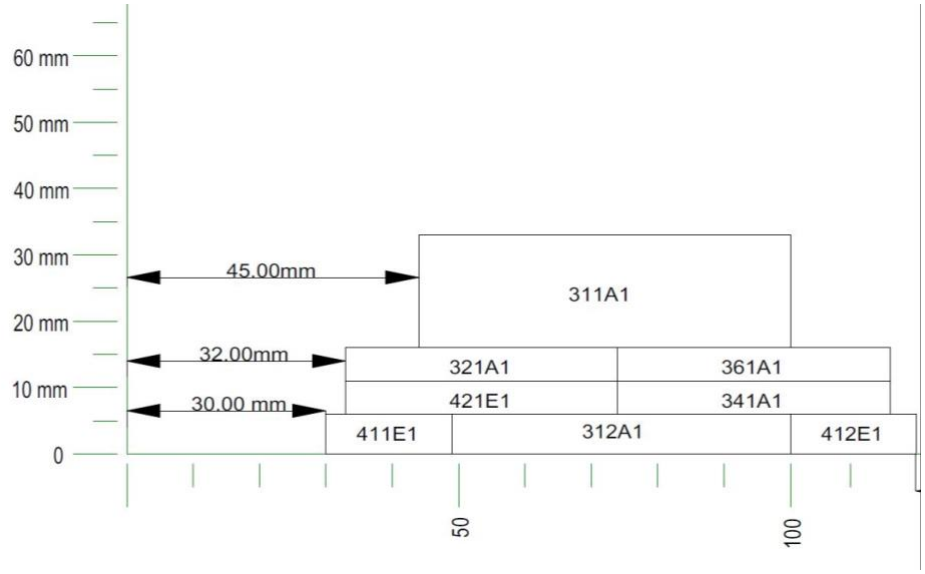

Figure 33. Cable placement tool in Microsoft Excel (Image credits: Konecranes).

Zuken E3.series is used for cable dimensioning and a separate Excel tool is used for cable package balancing.

Once the cable placement has been decided the designer can begin the calculation with loading the values to the tools.

Based on the cable package arrangement in Figure 33, the cable package height, the thickness of the largest cable, thickness of the cable package below the largest cable and width of the cable package can be obtained and the values are added to the tool. The weight of cables in kg/m can be obtained from the manufacture data sheets. Festoon location is added based on the exact location on the crane.

Table 5. Crane locations

Festoon location	Name
Crane Festoon	W1
Trolley festoon	W2A
Cabin festoon	W4
Pendant festoon	W3

Festoon Calculations for Trolley

Cable Specifications

Festoon location	W2A	
Cable package height (St)	33	mm
Thickness of cable package under the largest cable	18	mm
Thickness of the largest cable S2	15	mm
Cable package width (KB)	120	mm
Weight of the cable package	5	kg/m

Figure 34. Electrical Parameters for trolley calculations.

Note: The inputs from the user are denoted by the field with blue font whereas the calculated and fixed values are in black font.

The tool checks whether the KBK cable festoon system can accommodate the cable package of the given parameters. The maximum allowable limits are set in the tool for cable package height, cable package width and cable package weight. These parameters will be checked and if it is beyond the limit an error message will be displayed which would notify the designer regarding the constraints.

To demonstrate the working of the error message a dummy data has been added to see the error message. The maximum height that can be used on the cable saddle is 70mm. Hence for testing purpose a cable package of 90mm has been added to the calculation tool.

Cable Specifications	ERROR:MAX CABLE PACKAGE HEIGHT FOR KBK100 IS 70mm	
Festoon location	W2A	
Cable package height (St)	90	mm
Thickness of cable package under the largest cable	20	mm
Thickness of the largest cable S2	70	mm
Cable package width (KB)	80	mm
Weight of the cable package	10	kg/m

Figure 35. Error Message.

The error message is displayed as expected and this would serve as a warning system for the festoon designer.

If all the input parameters filled in tool are correct and within the working range, the tool then calculates and displays the cable trolley parameters are shown in Figure 36.

Dimension for Selected Cable trolley		
Cable trolley complete length	190	mm
Cable trolley length	160	mm
End clamp length Rail end clamp R62	190	mm
Saddle actual diameter	124	mm
Towing trolley length	190	mm

Figure 36. Dimensions data for trolley calculations.

The tool displays the component dimensions for cable trolley, towing trolley, and end clamp.

In future, if multiple cable trolley of different dimensions is added, the tool has the functionality to automatically choose the suitable cable trolley based on the given input parameters.

The festoon designer then inputs the values given mentioned in Table 4.

Initial data for Festoon		
Maximum loop height from beam	2080	mm
Traversing Distance(Li)	30000	mm
Trolley speed	20	m/min
Cable length at bridge end(Lb)	27000	mm
Cable length at trolley end Lt	11000	mm

Figure 37. Initial data for trolley calculations.

After filling all the values to the tool, we then receive an output in the form a table shown in Figure 38.

Output Data		
Number of cable loops N	9	
Binding distance Ls	4001,56	mm
Loop height from beam Hr	1960,78	mm
Number of cable trolleys N	8	trolleys
Gathering Length (calcualted minimum)	1854,0	mm
Gathering Length (manually defined)	2740	mm
Tension Factor P	1,1	
Festoon Cable Length Lf	36014	mm
Total length of cable Lc	74014	mm

Figure 38. Output of trolley calculations.

The tool provides the output data for implementing the cable festoon system.

The user has the option to enter the Gathering length manually defined. The calculated gathering length should be less than the manually defined gathering length and the manually defined length is preferred for further calculations.

Based on the values of load cycles the cable trolley's maximum loading can be defined. The calculations are performed to get the most optimum distance between the suspension fittings. An approximate value of 'distance between suspension fittings' is added to start the iterative calculations.

Load per trolley				
Cable trolley cycles		250000		
Cable trolley max loading		56	kg	
Calculated cable trolley loading		21	kg	
Total number of Cable trolleys		9	trolleys	
Distance Between suspension fittings		3000	mm	
Trolleys in section lw		9	trolleys	
Calculated cable trolley loading		20,4		25
Calble package		5,0	kg/m	
Maximum distance between suspension fittings	NOT SAFE	2	m	

Figure 39. Lw Trial 1.

If the assumed value is not correct the tool gives the user a warning signal. The designer then tries to lower the value till we get the "SAFE" signal from the tool.

Load per trolley			
Cable trolley cycles		250000	
Cable trolley max loading		56	kg
Calculated cable trolley loading		21	kg
Total number of Cable trolleys		8	trolleys
Distance Between suspension fittings		1000	mm
Trolleys in section lw		5	trolleys
Calculated cable trolley loading		20,0	25
Calble package		5,0	kg/m
Maximum distance between suspension fittings	SAFE	2,7	m

Figure 40. Lw Trial 2.

If the distance between suspension fittings is less, A 'SAFE' signal is displayed. But adding suspensions more than the needed value is not an economical choice. Hence, the values are fine-tuned till an optimal number is figured out.

Load per trolley			
Cable trolley cycles		250000	
Cable trolley max loading		56	kg
Calculated cable trolley loading		21	kg
Total number of Cable trolleys		9	trolleys
Distance Between suspension fittings		1800	mm
Trolleys in section lw		9	trolleys
Calculated cable trolley loading		20,4	25
Calble package		5,0	kg/m
Maximum distance between suspension fittings	SAFE	2	m

Figure 41. Lw Trial 3.

Once we get the "SAFE" signal we can proceed to calculate the crane festoon system. the steps are like the one used in trolley festoon calculations.

5 Conclusions

5.1 Summary

The objective of the thesis was to develop a calculation tool for designing the festoon system developed by Konecranes. The tool was then evaluated on an old project, and it was able to calculate optimum parameters which satisfied all the design constraints.

The tool was designed with an aim to calculate the solution for the parameters while still satisfying all the constraints. Without an optimum solution the crane festoon system would have a greater number of components which can increase the weight and cost of the system or a smaller number of components which increases the risk of design failure and accidents.

Also ordering a festoon cable of wrong length would result in total wastage as it cannot be easily used in any other projects. Ordering the exact number of components and avoiding wastage of expensive cables would prove to be very profitable. Due to the warnings available in the calculation tool a safe festoon system can be designed, and accidents can be avoided.

5.2 Limitations of study

The calculation tool is designed only for cable festoon system for Overhead cranes based on the dimensions of the components. The dimensions and design of the components, and the references from company files has not been mentioned in this thesis due to corporate policies.

While working on the formulas for the calculation tool, the closest approximate value must be considered for some section lengths of the cable. For e.g., in Figure 20 during gathering length, the top loop can be considered as a proper semicircle as it lies on top of a cable saddle, but the bottom loops cannot be considered a perfect semicircle while bending.

Due to this reason a buffer value needs to be added before ordering the cable. Festoon cables are expensive, and the leftover piece has no other use. Hence more data can be collected on the actual length of the cables used from the assembly team to reduce the error margin in the calculations.

The other limitation is that the calculation still involves human inputs like determining the cable placement, deciding the cable lengths at buildings and trolley ends which increases the possibility of error in the calculations. A solution for this issue would increase the accuracy of calculations and avoid component wastage and system failure.

5.3 Future studies

There is always a scope for improvement and a lot of design changes can be made on the KBK festoon system as well to make the system way better.

Some of the possible upgrades are as follows:

- Cable bracket to avoid the cables colliding with each other when gathered.
- The design of cable trolleys can be modified to avoid metal to metal contact which reduces the life span and would also ensure a quieter operation.
- Currently the lifetime of the festoon system or the components cannot be determined accurately. By collecting data over a period and using machine learning models the exact time for maintenance and component replacements can be found out which can prevent accidents.

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