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The Ropeless Elevator: New Transportation System for High-rise Buildings (and Beyond)

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Abstract

The paper reports the result of a 2-year long research conducted by CTBUH on the design possibilities enabled by the Ropeless and Multidirectional elevator systems, investigating how such a significant innovation (or better to say revolution) in the vertical transportation could affect tall buildings first and cities then. The purpose of the study is to prefigure the adoption of ropeless and multidirectional cabins for tall buildings mobility, with the aim to overcome the evolutionary bottleneck of the high-rise building type due to the exclusively vertical direction of transport, which limited, over the years, the design possibilities in terms of height, shape and relations with the surrounding environment. CTBUH research team, together with professionals in the field and supporting academic advisors, developed a series of design considerations on plan organizations, dispatching alternatives and on the integration of horizontal direction in the circulation, with the aim of anticipating potential and criticality arising from the application of ropeless and multidirectional systems.

Keywords: Vertical transportation, Elevators, Technology

1. Introduction

The close relationship between the high-rise building type and the passenger elevator, intended as a vertical transportation system, has been acknowledged by the most influential historians of architecture (including S. Giedion, C. Condit, F. Mujica, J. C. Webster, etc.) and professionals who, over the years, have dealt with the design of this building type (including H. L. Sullivan, R. Koolhaas, F. L. Wright, etc.). In fact, the passenger elevator is frequently recognized and labeled as one of the inventions, "breakthroughs" (Koolhaas 1978) or tools that made the modern skyscraper what is today.

"*What is typically not acknowledged is that the reverse is also true. The emergence of the skyscraper in the 1880s and 1890s fostered the development of the modern passenger elevator. What has been typically referred to as a 'chicken-and-egg history,' that the elevator came first and made the skyscraper possible, is perhaps better characterized as a symbiotic relationship. The elevator's technical history has revealed part of this story […]*" (Gray 2014).

Therefore, we can say that the building-elevator combination has gradually transformed into the skyscraper-elevator binomial thanks to, on one hand, the progressive and unceasing progress in the vertical transportation field and, on the other hand, the success that the high-rise building type registered over the years on a world scale. Moreover, what is even less acknowledged, is that the limits of one, either the elevator or the building type, directly affect the other and *vice versa*, in compliance with the "symbiotic relationship" identified by Gray. Of the two, the elevator is perhaps the one that imposes the greatest limits and constraints in this relationship.

2. The identification of the Evolutionary Bottleneck in Vertical Transportation

Whether it's about the fastest, the largest (in terms of capacity), the most efficient, or the "greenest," the operation of a passenger elevator still relies on the principle that E. G. Otis made safe more than 160 years ago: a cabin, hanging on a counterweight by means of a rope, which can move only vertically inside an exclusive and dedicated shaft through the building. In order to travel longer distances, and therefore to serve taller and taller buildings, the constitutive elements of the elevator must be specifically sized. However, as is well-known, there is a limit to the efforts and weight that these elements can support. For this reason, over the years, alternative solutions have been identified to reach higher levels, adopting some compromises.

The adoption of sky-lobbies and the hierarchization of the flows that organize the towers into sections served exclusively, thus offering a low-, mid- and high-rise service, are among the most widespread solutions. Other possible alternatives include the insertion of multiple cabins within a single shaft, such that the cabins can be combined in one

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unit (double-deck elevators) or disconnected and autonomous (such as the TWIN technology by thyssenkrupp). These solutions, although efficient from a transport management point of view, require a greater effort, especially for the users. The statement applies both in terms of time; for example, having to change from an express system to a local system to reach their destination; and in terms of users' understanding of internal mobility, which may not be immediately intuitive.

Given the success that the high-rise building type has had, and is still having, it is clear that the technological solutions and dispatching strategies implemented have been effective. However, in the course of the evolution of this building type, some problems arose. First among these is the unfavorable proportion between the "served" and "service" spaces that is, between the rentable and non-rentable areas. As mentioned above, in fact, as the building grows, the vertical transport system must be strengthened, in terms of capacity and power, and often fragmented, occupying considerable space within the service core. This, as can be seen in many floor plans, is to the detriment of the useful income-generating space. Finding the correct balance, in purely economic terms, between the two types of space has always been a crucial element in the design of the tall building. Examples of this can be found in many historic skyscrapers.

In the Empire State Building, Lamb (1931) points out that "*The elevator system was one of the keys to both the general arrangement of the plan and to the height to which the building could rise*." Even more representative is the case of the Equitable Building, conceived with the aim of being recognized as having "*[...] the best elevator service of any building in the world.... The elevator service will determine the height of the building*" *(*Weisman 1970). The proportion between rentable and non-rentable space is today still a critical point in the design of a skyscraper, and a balanced relationship between the two is not always achievable, given the size of these architectural giants.

A second critical point linked to the internal circulation system concerns safety, especially in the event of an emergency and the need to escape. The concept is simple: in a skyscraper the entry and exit points coincide. It follows that the interruption of an exclusively vertical circulation system, can compromise egress. The 9/11 event that hit New York City's twin World Trade Center towers tragically revealed this problem. Not surprisingly, some of the projects that were presented for the new One World Trade Center proposed horizontal connections to place several towers in communication with each other, thus multiplying the alternative escape routes. The horizontal connections, defined as skybridges, have experienced relative success, especially in recent years, becoming spaces for socializing, as they are equipped with various services, therefore representing an added value to the tenants or users of the building.

From the climbing walls of the American Copper Buildings in New York, passing through the panoramic swimming pool on the top floor of the Marina Bay Sands in Singapore, to the multifunctional belt of the Linked Hybrid in Beijing; skybridges seem to represent the new trend of the tall building, identifying a process of change from the previous singular towers that have characterized the skylines of many cities around the world. The Interlace (see Figure 1), Singapore, takes this design trend to extremes, earning the title of the CTBUH Urban Habitat Award in 2014, as "*it demonstrates dramatically the real opportunity tall buildings have for creating quality urban space at height, if we can only break down our preconception of designing skyscrapers as standalone, unconnected icons*" (Robinson and Wood 2014).



Figure 1. The Interlace, Singapore. (Source: wikicommons)

The question that arises looking at this new trend in the evolution of the high-rise building type goes back to the symbiotic relationship occurring with the elevator systems. *What is the role that the transport system can play in this?*

3. Ropeless and Multidirectional Elevator Systems

The passenger transport system, being still linked to the basic principle, is strongly constrained by its constituent elements. Recognized as a strong limitation, scholars and experts in the transport sector have always tried to go further and overcome its basic principle. The examples are numerous, starting from Sprague's Dual Car Elevator, conceived to

"[...] reduce the waste of space, by installing and operating on the same rails a pair of elevators in a common shaft, using common or separate counterweight rails for both elevators, any shaft being thus available for elevators running from the main floor to supply local service to two different floor zones, with express service to the lower floor of the upper zone" (Sprague 1930).

Moving to the Paternoster, also called a "cyclic passenger

elevator" or "perpetual elevator," which experienced considerable success, especially in Germany, where it was installed in low-rise multi-story office buildings (Lampugnani and Hartwig 1994). The Paternoster fell into disuse for safety reasons, as passengers literally had to jump in and out of the constantly moving doorless cabins. Looking at even more extreme solutions, that have totally questioned the concept of internal circulation in a tall building, the Odyssey system must be mentioned. Proposed by Otis in 1996, it is an integrated system designed for

"*[...] building as high or as wide as you like. You can interconnect structures. You can dictate configurations, performance and dispatching characteristics. And you can count on lower construction costs and larger interior volumes; an Odyssey system eliminates hoistways and machine rooms that consume valuable, rentable space...*"

as reported in the presentation brochure (Koolhaas and Boom 2014). It was conceived as an integrated system where the cabins, released from cables and counterweights, can follow both vertical and horizontal paths. Fortune (1988) describes it as a combination of a conventional elevator and an automated people mover. Otis proposed a further application scenario on an urban scale, assuming the creation of communication systems between buildings, or even between public transport systems and the internal circulation of buildings (McCarthy et al. 1996). A 1:1 scale prototype of Odyssey was built in the Otis Center in Bristol, Connecticut, where users could see the various elements of the plant and follow some explanatory films (Koolhaas and Boom 2014); however, it was never applied in a building, probably for economic reasons (Barker 1997).

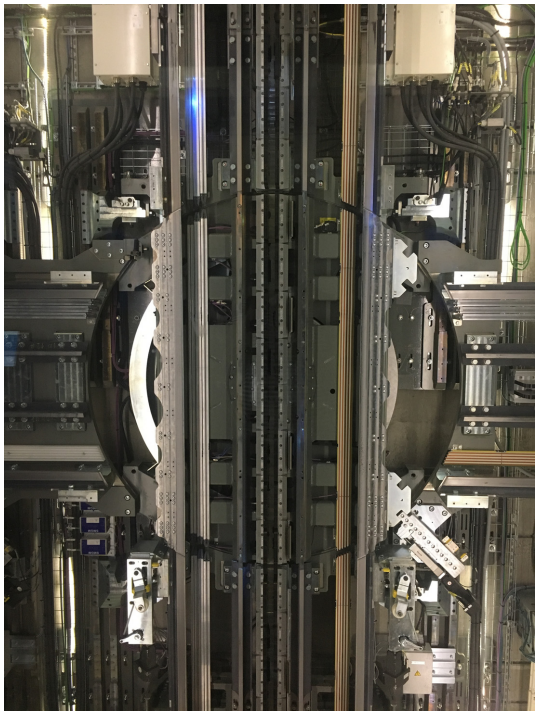


Figure 2. The rotator of the MULTI system developed by thyssenkrupp and installed in the test tower in Rottweil, Germany. (Source: Martina Belmonte)

More recent and equally revolutionary is the MULTI system announced by thyssenkrupp in 2014 and officially presented in Rottweil in Germany in 2016, where it was installed in the Test Tower (see Figure 2). In this case as well, the cabin is completely free from ropes and counterweights, because it moves thanks to a linear induction motor along the metal guides that identify the paths. The cabin can therefore follow both vertical and horizontal (hypothetically also diagonal) paths, thanks to the insertion of rotating elements, called exchangers, which give continuity to the path. It is "[…] a circulating, ropeless multicar elevator system that eliminates the limits and disadvantage of traditional shuttle elevators and also enables more flexible arrangements" (Jetter and Gerstenmeyer 2015).

The new technology combines the TWIN system, in which multiple cabins move independently within the same shaft, together with the Paternoster concept, as an enclosed, multi-car circuit. The main difference is that, here, the cabs are completely independent from ropes and counterweights. This means that multiple cabins can travel at the same time within the same circuit, even if one moves upward and one downward in the same shaft. The number of cabins in circulation will be proportionate to the demand, providing savings saving in terms of space. An early application could be to combine the MULTI system with pre-existing strategies, using it as a continuous system to put successive sky-lobbies in communication, and thus acting as an express system. An immediate advantage, given by this configuration, lies in the reduction of the number of shafts, since a greater number of cabs can travel simultaneously within the same circuit. The role that its installation in the design of a tall building has a revolutionary potential; it could be a game-changer in future high-rise development.

A research group of the Council on Tall Buildings and Urban Habitat (CTBUH) investigated the potential consequences in the design of a tall building deriving from the application of a ropeless and multidirectional technology (thus referring to MULTI, Odyssey and other devices). The research lasted two years, and as a result of this study, some design considerations were put forward that highlighted both the potential and the critical points deriving from this operation. It involved various international professionals, involved at different stage in the definition of a tall building project, including architects, vertical transportation experts, structural engineers, constructors, etc. Some of the most relevant results are briefly reported in this paper, organized into three different sections, in line with the focus points adopted in the CTBUH Research project: impact on the floor plan organization, alternative dispatching strategies, and the integration of horizontal movement.

3.1. Impact on Floor Plan Organization

The study started by questioning the difference in the operation of a ropeless and multidirectional system, as compared to that of a conventional elevator. The very first, and substantial, difference was in the loading and disembarking process. In a conventional elevator, the users call the elevator via a push button, and use the very first cabin approaching, in which they can then indicate their destination. This basic principle has been developed in tall and complex buildings, adopting (as already mentioned) the organization of flow into banks of shafts and, in some cases, managed by a destination control technology. However, the cabin that moves within a shaft can be used for both upward and downward direction; therefore, the loading and disembarking areas are the same.

A ropeless configuration can be set into an enclosed circuit, where one path or shaft is exclusively used for the upward travel, while another one for the downward (see Figure 3). It must be explicit and clear to the users which is which; according to their direction, they need to identify the proper line, in the same manner as one uses a metro transport system.

This led to another possibility, namely the spatial separation between the two lines (see Figure 4). The circuit is here represented for simplicity by just two lines (although at least three are recommended), where the loading and disembarking areas can be distinguished by either using a signage or a signal, or completely separated one from the other and spaced apart. In reality, the two vertical lines are clearly connected by the horizontal line, which is placed at other levels.

Also, the horizontal path has been taken into consideration in the study. Taking ski facilities as reference, it was suggested to arrange a horizontal progressive loading (disembarking) area (see Figure 5). As in a ski lift, the cabins (maybe combined in a train of 3-4 cabs) can move slowly, allowing a major volume of users to get in and out, thus improving the management of the people flow. This solution may be very useful in crowded buildings (think about the advantages during the morning up-peaks)

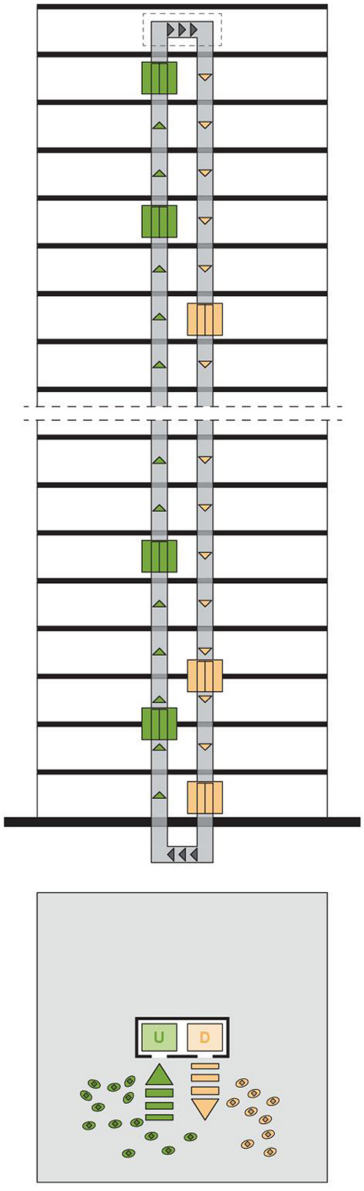


Figure 3. A ropeless and multidirectional configuration, both in section and in plan. (Source: CTBUH Research team)

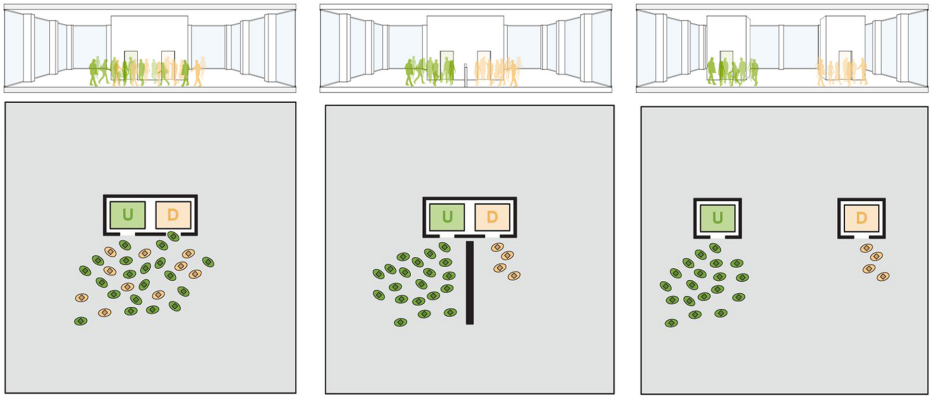


Figure 4. Alternative configuration of the loading and disembarking areas due to the application of a Ropeless and multidirectional system. (Source: CTBUH Research team)

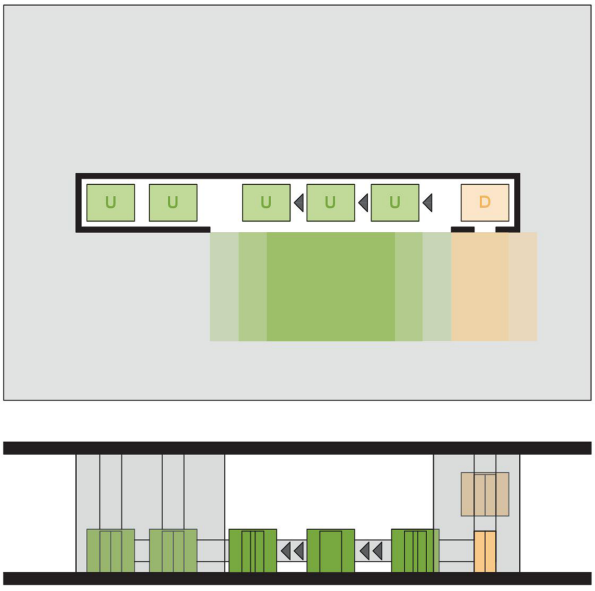


Figure 5. The progressive loading arrangement. (Source: CTBUH Research team)

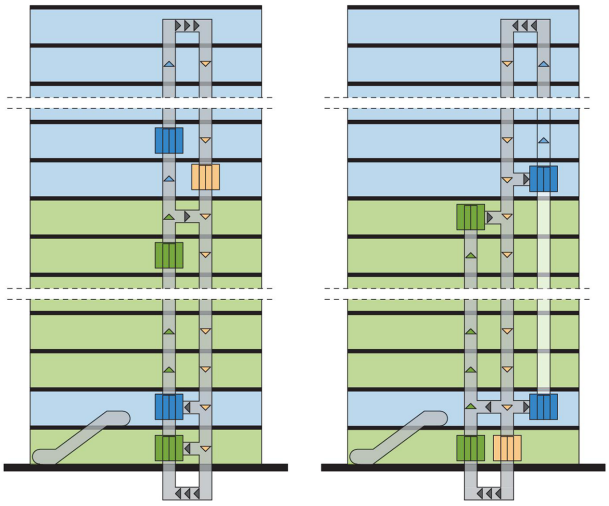


Figure 6. The application of a ropeless system in a multipurpose building. The loading areas are separated at different levels, but the cabins can travel along a shared circuit, affording a significant savings of service space. (Source: CTBUH Research team)

but also in metro stations, allowing train passengers (at a consistent volume) to quickly reach the exit.

In a tall building, the separation of the flows is quite common, such as with multi-purpose or multi-tenant buildings. Usually, it leads to the separation of the entrances and, therefore, of the elevator banks along the perimeter of the tower or using alternate floors, connected for example with escalators. This strategy, however, requires a consistent amount of space, given that each flow requires different entrances and banks of elevators. In the hypothetical application of a ropeless elevator, the space required could be significantly reduced, thanks to the cabins' sharing the same circuit. The loading and unloading areas can be kept separate (see Figure 6), but the cabins can travel along the same circuits, reaching their assigned destinations.

In a tall building the need to distinguish and spatially separate the flows is quite common, most of all in the case of multi-purpose or multi-tenant towers. It is usually convenient to separate them at the very beginning, arranging different entrances along the perimeter, or at different floors of the building. As Figure 6 shows, such separation can be supported and assured with the application of a ropeless system, leading to some advantages. In a conventional system, the different flows require different shafts and banks, thus occupying a consistent amount of space. In a ropeless configuration, while the loading areas can be separated, the cabs can then travel along the same circuit, therefore saving space and ensuring an effective transportation service.

3.2. Dispatching Considerations

The study moved then moved on to the dispatching strategies that a ropeless and multi-directional elevator system can allow. Both solutions to support existing and completely innovative alternatives have been taken into account, in order to investigate as many solutions as possible, identifying potential and critical issues. To this aim, some basic schemes have been developed and

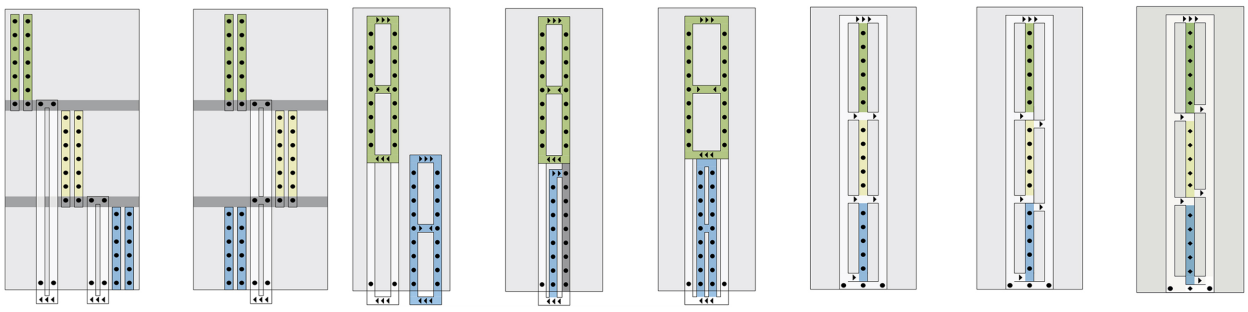


Figure 7. The alternative integration of the ropeless and multidirectional elevator system in the internal circulation of a tall building project. In the first two, an integration between the ropeless and the conventional system is proposed. In the others, some hypothetical dispatching solutions, completely entrusted to the ropeless technology, are identified. (Source: CTBUH Research team)

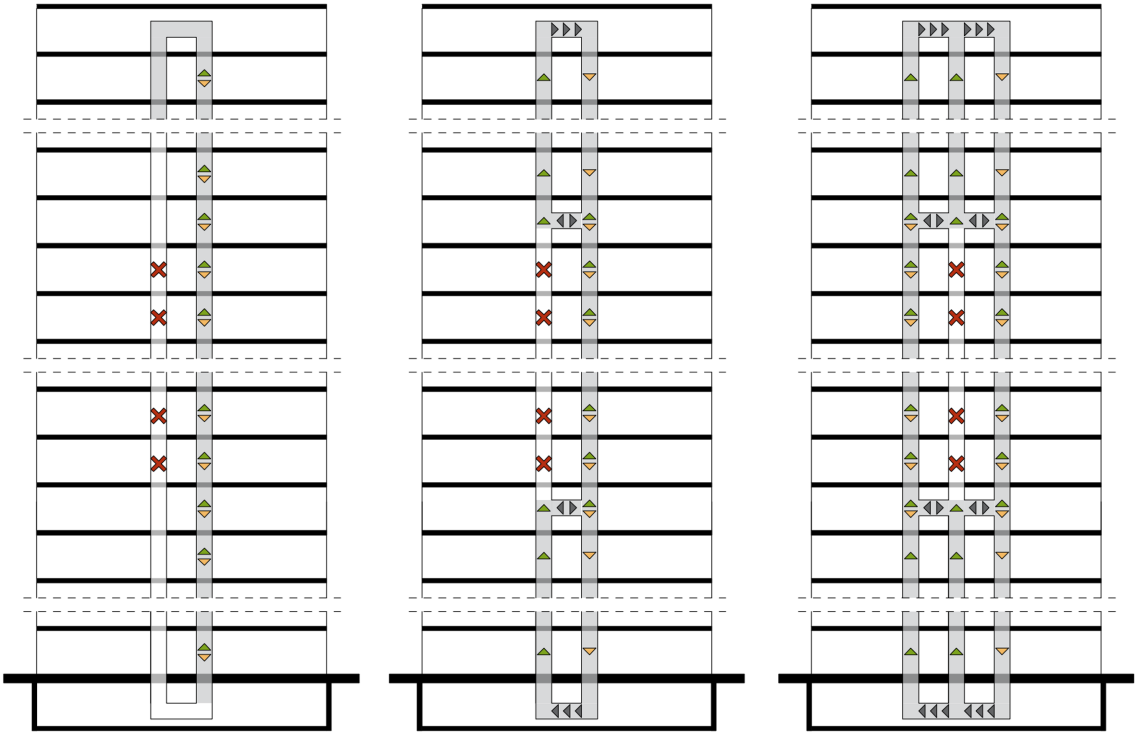


Figure 8. In the case in which a portion of the circuit is out of service, the presence of horizontal connections is fundamental to creating alternative routes, ensuring the efficiency of the transportation system. (Source: CTBUH Research team)

discussed with the professionals involved (see Figure 7).

In a very first approach, the ropeless elevator has been conceived as a support element to combine with the conventional vertical transportation. In fact, as Figure 7 shows, the circuit acts as a direct connection between the subsequent skylobbies, where the users still need to get off the cabs and reach the local service. In the other concepts, instead, the ropeless application has been pushed further, entrusting the entire trip to the technology. In the various loop configurations identified, in fact, the cabs are responsible for both the express and the local service in the assigned sections into which the tower is divided. In the most "extreme" and proactive configuration, the different flows, the express and the local services are all combined within one, more complex, circuit. The location of the horizontal connection is strategic, and must be seen as the key element of this new technology.

Such awareness led to a further important consideration: the optimal implementation of the horizontal connections for a more efficient and safe circulation. In fact, a higher number of horizontal connections means more alternative routes, which can be useful in the event that there is a malfunction of some parts, or maintenance interventions are required (see Figure 8).

An equally important and noteworthy result concerns the provision of storage and parking areas along the building, which is made possible by the horizontal translation capability of the cabins. In such spaces, the cabs can be parked while waiting to enter the circuit, for example, during the morning up-peak when a higher demand is required. At the end of the peak, the cabs can return to the parking area, waiting to be called again. Moreover, such spaces can also be arranged for maintenance.

3.3. Integration of the Horizontal Direction in the Internal Circulation

Recognized the horizontal movement as the key element of this technology, and keeping in mind the "symbiotic relationship" between the building and its transportation system, the study also evaluated considerations in this dimension. As can be seen, the skybridges are growing in prominence in the tall building design of the last few years, and the possibility of connecting two or more towers has a relevant role in terms of safety. So far, however, the passenger elevator has not had a specific role in this, as it has been limited by ropes and counterweights to exclusively vertical motion. Freed from such constraints, horizontal movement is finally a possibility. On this theme, the study proposed a series of possible integrations of the transportation system within the horizontal skybridges (see Figure 9).

This could have an incredible impact on the way tall buildings are designed and conceived. Beyond this, given that more parts of the city and more services could be put in direct communication, think for example of the public transport system. These considerations were advanced thanks to the study that was conducted on the various patents and projects of unconventional transport systems

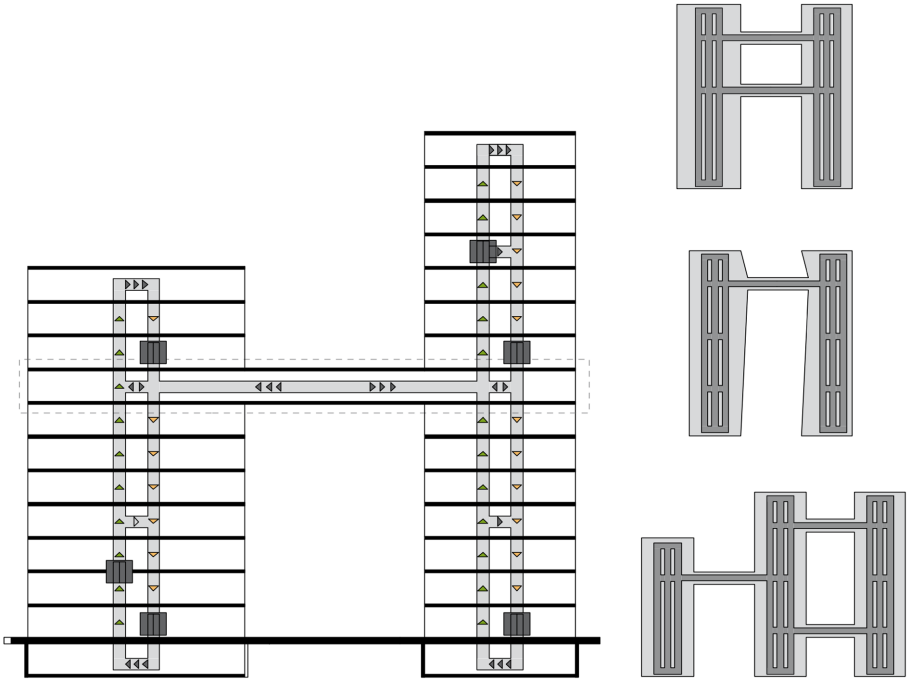


Figure 9. The skybridge hosts the horizontal path of the ropeless system, directly connecting the circulation systems of two or more towers. (Source: CTBUH Research team)

conceived in the past (for example, Odyssey), but also taking into consideration the technological advances achieved.

The study proposed some alternative applications of that which has been described above (see Figure 10). In the first case, the ropeless system allows the total use of the space below, so that the passengers can see what happens in the skybridge, and some areas where they can get in and out of the cabins can be provided along the path. In the second case, one of the two lines is located near the facade of the skybridge, so that passengers can observe the panorama flowing in front of them.

4. Final Considerations

What has been presented above is just a portion of the design consideration identified during the two-year research project conducted by the CTBUH team. All the results and findings have been deeply discussed with tall building industry professionals, who have been involved at different stages during the research. The potential that such a revolution in the transport sector would have is substantial, and it is certain that it would not be only tall buildings that would benefit. Public transport systems, for example, could be strengthened and put in more direct communication with the circulation inside the buildings, almost without interruption of continuity. Special applications were also hypothesized during the research, such as the integration of a private system with a public one within the same circuit. One system that serves residences and another that, instead, is dedicated to public spaces or other functions, could coexist and optimize the use of space by circulating in the same route.

Applications in healthcare have also been hypothesized. In healthcare buildings of considerable size, for example, the presence of ropeless and multi-directional cabins could be of great advantage. Conceived as internal "ambulances," they could be suitably equipped, and lead patients and staff where necessary without ever having to get out of the cabin, reducing waiting times, walking distances and ensuring greater safety, especially for patients, who will always remain in a controlled environment.

Other considerations concern safety and the methods of intervention in a ropeless and multidirectional circuit. For example, special booths have been designed that can approach those in "difficulty", or that in any case require assistance, providing operators new ways to intervene.

An important result, then, concerns the critical points and limits that have been defined. In fact, although the advanced considerations demonstrate the revolutionary potential of these new technologies, underlining the need for renewal in the sector, it is equally true that some critical elements have been found.

In the first place, but not the subject of the study, the technical and development aspects of the technology are currently still being defined, probably due to the fact that there are no "precedents" to deal with, and/or legislation to which to refer. The definition of "elevator" refers to ropes, counterweights, and motors-all elements that this new device does not possess.

Another big obstacle, which must be faced in a proactive way, concerns the interaction and communication

with the user. The use of the lift is part of the daily life of most people in the world, so much so that it is natural to know how to use it. A ropeless lift has a completely different operating principle. It therefore follows that it will require both a period of adaptation, but also, and above all, a greater effort on the part of designers and experts to make this new device user-friendly and easy to understand.

The research proposes some possible solutions to achieve this goal, which are based on an effective and direct communication that informs the user of the various stages of the journey. The user needs to be informed of the approach of the car, the fact that there is another one in the queue, how much time elapses between the two, how it moves along the path that is no longer straight, how much time is left to the destination, and so on. Also, because the cabins, having to change direction, will probably not be able to travel at high speeds like today, so travel times will be extended. For this reason, among the various proposals, the idea was also advanced of equipping the cabins with interactive services, which allow passengers to "get distracted" during the journey, given that, as is known, staying too long in the confined interior of an elevator car is uncomfortable for many people.

To conclude, the main result of the research conducted is that, to ensure the success of this technology, once made available on the market, the main objective should be to regain the trust of users, as has happened over time with conventional lifts. Once this is done, the expressive and applicative possibilities could potentially be limitless, bringing the symbiotic relationship of the binomial to a later stage, perhaps more in line with the needs of dynamism and movement of modern society, recalling the utopian city projects of H. Corbett, M. King, or L. Hilberseimer, and others who foreshadowed an urban settlement characterized by fluid and layered connections.

Acknowledgement

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