Institution: University of Northampton		
Unit of Assessment: 12 - Engineering		
Title of case study: New Design Guidelines to Optimise the Dynamic Performance of Vertical Transportation Systems in High-Rise Projects Worldwide		
Period when the underpinning research was undertaken: 2010-2019		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
1. Stefan Kaczmarczyk 2. Philip Picton 3. Huijuan Su	1. Professor 2. Professor Emeritus 3. Senior Lecturer	1. 2005 - present 2. 2005 - 2017 3. 2016 - present
Period when the claimed impact occurred: 2013-2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

Research led by Professor **Kaczmarczyk** has resulted in the development of robust algorithms to analyse and control the dynamic behaviour and interactions taking place in Vertical Transport (VT) systems. The majority of the work has been carried out within the framework of the **Partnership for Research and Innovation** between the University of Northampton (UoN) and **ThyssenKrupp Elevator** (TK Elevator). The research has resulted in the formulation of design guidelines to solve complex technical problems, which have been applied in TK Elevator VT projects worldwide. These have transformed the company's Engineering practice and capacity of designing safety standard-compliant high-rise lift installations in major building projects worldwide.

2. Underpinning research

In the modern built environment VT systems such as lifts (elevators) service buildings that are nearly 1000m high. Tall buildings are susceptible to large sway motions when subjected to wind loading and long-period seismic excitations. In a scenario where a building is subjected to fundamental structural resonance, low frequency sway motions of the building take place. These in turn form base-motion excitation to elastic components of the VT installation causing nonlinear resonance interactions in the lift car/counterweight systems **[3.1, 3.2]**. The resonance interactions affect passenger ride quality and result in a high level of dynamic stress **[3.3]**.

The underpinning research involved fundamental studies into the modelling and control of nonlinear, stochastic, time-varying systems **[3.4]** to gain an understanding of how deterministic and random excitations affect the operation of VT installations **[3.5]**. Experimental studies and testing were carried out to identify the dynamic characteristics and parameters of key components of VT systems **[3.6]**. Theoretical models of entire VT systems were then developed and validated to predict the resonance interactions in these systems **[3.2, 3.3]**.

This work has led to the development of bespoke simulation software tools to quantify the transient and steady-state resonant responses taking place in high-rise lift applications **[5.1]**. The results facilitated the development of design guidelines and strategies to minimize the effects of adverse dynamic responses so that the installation would operate without compromising the structural integrity and safety of the system **[3.1, 3.2, 3.3, 5.1]**. The key guidelines and strategy have been as follows:

- The fundamental vibration modes of the building structure and the VT system should be considered in the analysis.
- The resonance frequencies of the lift suspension system and compensation system should be calculated over the entire range of lift travel and simulation tests to predict their dynamic responses when the car is positioned at critical points in the well must be considered.
- The key dynamic characteristics of the lift system should then be adjusted and optimised to shift the resonance conditions so that sufficient safety margins are maintained.
- The minimum factors of safety and the traction conditions/ requirements must then be checked in order to satisfy the safety regulations prescribed by relevant safety codes.

The application of relevant passive (e.g. hydraulic tie-down device) and active (e.g. active stiffness) vibration control strategies can be effective in reducing the resonance motions taking place in the elevator system.

3. References to the research

[3.1] Kaczmarczyk, S., & **Picton, P.** (2013). The prediction of nonlinear responses and active stiffness control of moving slender continua subjected to dynamic loadings in a vertical host structure. *International Journal of Acoustics and Vibration*, *18*(1), 39-44. https://doi.org/10.20855/ijav.2013.18.1318

[3.2] Kaczmarczyk, S. (2020). The Dynamic Interactions and Control of Long Slender Continua and Discrete Inertial Components in Vertical Transportation Systems. In A. Abramyan, I. Andrianov, & V. Gaiko (Eds.), *Nonlinear Dynamics of Discrete and Continuous Systems* (1 ed., Vol. 139). (Advanced Structured Materials; Vol. 139). Springer International. https://doi.org/10.1007/978-3-030-53006-8

[3.3] Sánchez Crespo, R., **Kaczmarczyk, S.**, **Picton, P.**, & **Su, H.** (2018). Modelling and simulation of a stationary high-rise elevator system to predict the dynamic interactions between its components. *International Journal of Mechanical Sciences*, *137*, 24-45. https://doi.org/10.1016/j.ijmecsci.2018.01.011

[3.4] Kawaguti, K., Terumichi, Y., Takehara, S., **Kaczmarczyk, S**., & Sogabe, K. (2007). The study of the tether motion with time-varying length using the absolute nodal coordinate formulation with multiple nonlinear time scales. *Journal of System Design and Dynamics*, *1*(3), 491 - 500. https://doi.org/10.1299/jsdd.1.491

[3.5] Kaczmarczyk, S., & Iwankiewicz, R. (2017). Gaussian and non-Gaussian stochastic response of slender continua with time-varying length deployed in tall structures. *International Journal of Mechanical Sciences*, *134*, 500-510. https://doi.org/10.1016/j.ijmecsci.2017.10.030

[3.6] Arrasate, X., **Kaczmarczyk, S.**, Almandoz, G., Abete, J. M., & Isasa, I. (2014). The modelling, simulation and experimental testing of the dynamic responses of an elevator system. *Mechanical Systems and Signal Processing*, *42*(1-2), 258-282. https://doi.org/10.1016/j.ymssp.2013.05.021

4. Details of the impact

The impact originates from the continued research collaboration with TK Elevator carried out within the framework of the Partnership for Research and Innovation agreement**.** Thus, the claimed impact forms a continuation from the case study submitted in 2014. The impact has been fundamental for the company's technical capacity to design safety standard-compliant high-rise lift installations during the period when the claimed impact occurred **[5.1]**. Research-led changes in their design practice have generated new projects and revenues, strengthening the engineering know-how of the company:

'Without the support of your research and advice, we would not yet be on the level of product design and engineering know how, which enables us to supply elevators for the highest buildings in the world.' **[5.1]**

Guidelines for Lifts in High Rise Buildings

Kaczmarczyk and colleagues developed new algorithms to analyse and understand the dynamic behaviour and interactions of VT systems with host building structures. This has led to the development of new design guidelines that were adopted by TK Elevator which changed the company's rules for the design of high-rise elevator installations to develop products for tall buildings:

'*the cooperation with you enabled our company to develop standardized products and design rules*.' **[5.1]**

Kaczmarczyk designed bespoke software tools **[5.1]** to predict the influence of tall building sway induced by wind forces and seismic excitation on VT suspension means and compensating system **[5.2]**. These have been applied to design elevator systems for buildings of over 250 m tall in competitively short times:

'Another 5 years later in 2019 the next milestone, 30 Hudson Yards, was opened. … the completion time … ***decreased by 50%*** *(from 10 years to 5 years). The main effect for the time shortening was in the area of theoretical fundaments and conceptual design.'* **[5.1]**

Kaczmarczyk then spearheaded further work and developed effective strategies to mitigate the effects of resonance conditions arising in the system. This has led to collaboration with the TK Elevator Global Research & Development department and to the formulation of global building sway guidelines based on the strategies and simulation tools developed by **Kaczmarczyk**:

'This resulted to the formulation of global design guidance rules which would not be possible without the research led and carried out by you and your team.' **[5.3]**

The guidelines allowed the company to improve the structural integrity and safety of high-rise VT systems. TK Elevator were able to provide their customers with high-rise products of superior performance and lower operational costs leading to increased customer satisfaction:

'The benefits involved a reduced need for replacing key components …. The main aspect has been the reduced ropes' wear which resulted in approx. 15% – 20% higher service lifetime, meaning the lower exchange cost. … improved methodologies around the dynamic response of the system decreased the potential for damages to the lift shaft equipment. If occurring, these damages can result in high repair costs.' **[5.1].**

This in turn has improved the marketability of products and has led to additional contracts and significant economic returns and new sales. For example, after the design guidelines were implemented to complete the One World Trade Centre in New York in 2014 and multi-million maintenance contract was then awarded:

'*Consider as an example your past and more recent work on building sway at the One World Trade Centre in New York. … the annual service contract was around US$5,000,000 per year.*

However, this impact, while significant, it still does not include the benefits due to the knock-on effects. These effects involve many additional significant orders that were received because in bidding for new projects we could say "We are the firm selected to provide the lifts for One World Trade Centre."' **[5.3]**.

New Projects/ Contracts and Patents

The guidelines developed by **Kaczmarczyk** have been used by TK Elevator design team to develop new projects and to attract new contracts. The guidelines have been applied in a number of prestigious elevator/ VT projects worldwide during the census period, including, Rottweil Tower, Germany; One World Tower, New York, USA; 30 & 50 Hudson Yards, NY, USA **[5.1, 5.3].** This stimulated the company's growth over the census period:

'In the related market segments, we then achieved an annual growth of more than 25% *on average in the period of 2013 to 2020.'* **[5.1]**

Furthermore, the research and latest generation of the building sway software for prediction of the dynamic responses of VT systems in the areas affected by environmental phenomena such as high winds and earthquakes resulted in new patents and provided the company with exclusive rights to develop effective control strategies. During the census period patents were awarded in the US and Europe for innovative efficient and cost-effective active vibration control system to minimise the effects of building response on the elevator system **[5.4, 5.5]**.

5. Sources to corroborate the impact

[5.1] Testimonial #1: Head of IP Management R&D, TK Elevator GmbH, Essen, Germany
Contact details: Martin Hochheuser, M: +49 172 212 1019,
Martin.Hochheuser@TKElevator.com

[5.2] Applied Joint Research and Development Project Agreement, 12 May 2020, thyssenkrupp Elevator AG / the Faculty of Arts, Science and Technology, University of Northampton.

[5.3] Testimonial #2: Technical Fellow, thyssenkrupp Elevator AG, Asia Pacific Office (formerly Director of Strategic Development, ThyssenKrupp Elevator Americas)
Contact details: Dr Rory Smith, M: +1 619 309 6385, rory.smith@tkeap.com

[5.4] European Patent**:** Kaczmarczyk, S. and Smith, R. (2016) Elevator System. 21 September 2016. Patent No: EP2913289 B1.

[5.5] United States Patent: Smith, R. and Kaczmarczyk, S. (2018) Elevator System, 16 January 2018. Patent No.: US9,868,614 B2