MBSE for Elevators - Reimagining Vertical Transportation

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Abstract

The urbanization requires society inhabiting in vertical landscape of building which makes elevators necessity for daily life. This modern elevator system is a complex integration of mechanical, electrical, control system and embedded software working together for required functionality. The proper intended functioning of system can be achieved by aligning all different requirements and limitations of different stakeholders and by adopting methodology of working. Traditionally all requirements, specifications are handled using documents which struggle to manage the complexity and are prone to errors, inefficiency and have large product development cycle. This paper highlights an alternative improved transformative paradigm approach of handing product development life cycle known as Model-Based System Engineering (MBSE). It uses model-centric approaches starting from requirement gathering to final system acceptance testing. It helps in improved requirement traceability, early validation of components and system behaviour enhance team collaboration and can help to build safe, reliable and innovative elevators.

1. Introduction

Elevators are essential means of transportation for taller building and structures. The demand of these elevators is increasingly exponential with urbanization which in turn requires innovative vertical transportation modes. The modern elevators need to design with higher speeds, greater capacities and feature of early detection of failures to avoid breakdown. Also, next-gen smart elevators are continuously communicating with building management system using IoT to collect sensor data, remotely controlling and monitoring elevators, improved efficiency and cost savings techniques, enhanced user experience and new business model and services.

Historically system engineering plays crucial role in developing elevators systems using document- centric approach. Although this approach is proven it lacks in handling increasing complexities and cross functional stake holder management and agile approach of working. The document centric approach led to inconsistency, misinterpretations of requirements, and lags in traceability (Ref. [1]).

Model-Based System Engineering (MBSE) evolved as powerful approach of handling all the limitation of system engineering. It uses formalized application of model-based approach starting from system requirements, system & architecture design, analysis, verification and validation starting from conceptual phase and overall lesser product development life cycle. It enhances clear understanding of system, helps in early detection of issues and streamline the entire development of complex system like elevators (Ref. [2])

This paper helps to explore benefits of MBSE over traditional document-centric system engineering approach and articulate core principle of MBSE in elevator domain. It demonstrates practical application of MBSE, highlights its benefits and reasons for successful adaption across the industries.

2. Challenges in Traditional Elevator Development Process

The elevators are developed traditionally using system engineering approach relying heavy on documentation and have following difficulties:

- **Ambiguity and Misinterpretation:** According to Davis and Miller (Ref. [3]), earlier all the system and component level requirements and specification of various stakeholders are maintained using text-based documentation. This text-based documents need to be maintained periodically, and many times led to confusion and ambiguity between different stakeholders. The ambiguity in understanding of documentation results in design flaws which are many times discovered during prototype building or during deployment (Ref. [4]).

- **Traceability Issue:** Text-based documentation is inefficient in maintaining history of change in customer requirements. It's become difficult to identify all the components affected with change in requirements and thus are susceptible to error prone (Ref. [1]).

- **Siloed Development:** According to Johnson and Williams (2021) (Ref. [1]), The elevators are built with different engineering discipline (mechanical, electrical, software, safety and production) working in silos. All these disciplines have their own set of design requirements which needs to be integrated to meet common system level requirements. This siloed approach makes integration challenging and incompatibilities between different disciplines requirement are identified in late development cycle leading to high cost of rework.

- **Growing Complexity:** Modern elevators are cyber-physical systems which involves intricate interactions between mechanical components (cables, cabin and motor etc.), electrical systems (power, sensor and invertors etc.) and software (user interface and connectivity). Handling this multi-discipline complexity is very difficult with text-based documentation and disconnected diagram are error prone.

- **Verification and validation at late stage:** Issues in traditional document centric approach are found late in the development cycle during prototype building and physical integration and testing where the cost of rectification is higher.

- **Limited Reuse:** Design elements and architectural patterns are often re-created for each new project, limiting the ability to leverage previous successful designs and intellectual property effectively.

- **Efficient change management:** Managing changes across numerous documents and ensuring all affected parties are updated and aligned is a significant overhead, often leading to version control issues.

These challenges underscore the need for a more integrated, systematic, and model-centric approach to elevator system development.

3. Introduction to Model-Based Systems Engineering (MBSE)

Per INCOSE SE Vision 2020 (INCOSE, 2007 Ref. [5]) MBSE is defined as "the formalized application of modelling to support system requirement, design, analysis, verification and validation activities beginning in the conceptual phase design and continuing throughout development and later life cycle phases. It is a paradigm shift in system engineering that emphasized the creation and exploitation of interconnected digital system models as the primary means of information exchange and understanding, replacing traditional document centric approaches. At its core MBSE is all about:

- **Model as Primary Artifacts:** MBSE approach uses comprehensive model as source of information instead of documents. The model centric approach helps to clearly understand the interface behaviour between different discipline, capture requirements of different stakeholders and architecture.

- **Standard Modelling Language:** MBSE utilizes standardize standard modelling language like SysML, which is designed to support system engineering activities and enhances accuracy, consistency and collaboration across teams.

- **Holistic View:** MBSE provides a multi-dimensional view of the system, allowing stakeholders from different departments to understand the system from various perspectives while maintaining underlying representation.

- **Simulation and Analysis Tool:** MBSE often uses simulations tools for component and system testing and analysis. It can be used build digital twin model of any system and associated objects. Digital twin model serves as dynamic copy of testing to see how system behaves under different conditions and helps to identify potential issues and optimizes performance.

- **Enhance Traceability and Impact Analysis:** The limitation document-centric method of unable to trace change request and perform impact analysis of changes can be overcome by MBSE. MBSE can help to build models linked to requirements and can test component and system behaviour and can perform impact analysis for changes.

- **Early and Continuous Validation:** Virtual executable models and simulations enable early analysis verification and validation of design alternatives and system behaviours long before physical protype is build or testing is done.

- **Improved Communication and Collaboration:** A shared model facilitates clear communication among diverse disciplines reducing misalignment and fosters a collaborative environment.

- **Automation Potential:** The formal nature of models enables automation of tasks such as code generation, test case generation, and documentation generation.

MBSE provides a structured, disciplined, and rigorous approach to tackle the increasing complexity of modern systems, making it highly suitable for the intricacies of elevator design.

4. Applying MBSE to Elevators

The growing demands of buildings, shopping malls and structures requires building smart and safer elevators. As the complexity and competition increases among industry adopting documents centric approach can result in higher product life cycle and difficulty in managing stakeholders with different requirements.

Implementing principles of MBSE across elevator industry can help to optimize the components used, manage complexity and can also help on team collaborations.

4.1. Requirements Management: Figure 1 shows three main pillars of MBSE.

- **Model-based Requirements:** Instead of a text document, requirements are captured as explicit elements within the system model. These can include functional requirements (e.g., "Elevator shall transport 10 passengers"), non-functional requirements (e.g., "Max acceleration shall not exceed 1.2 m/s^2"), safety requirements (e.g., "Emergency stop shall activate within 0.5 seconds"), and performance requirements.

- **Version Control Managements:** The models and requirements are managed using version control approach. The versions are maintained which keep history of all the updates done in each version, maintain data integrity, allow multiple users to work on the same model concurrently and helpful to revert to previous versions in case of unwanted behaviour.

- **Traceability:** MBSE tools directly link requirements to the system model enabling tracing from high-level needs to detailed design and even test cases. It provides real-time visibility into the system models, allowing continuous monitoring and management of requirement and design changes.

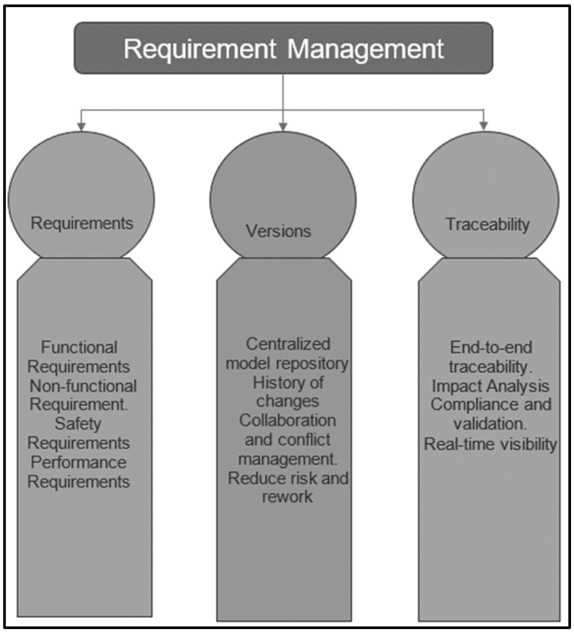

Figure 1: Requirement Management using MBSE for Elevator

4.2. System Architecture Design

- **Structural Modelling:** MBSE allows engineers to create structural model of elevator using SysML. SysML Block Definition Diagrams (BDDs) are used to define the components of the elevator system (e.g., control unit, motor, car, hoistway, sensors, doors) and their hierarchical decomposition. Internal Block Diagrams (IBDs) illustrate the internal structure of blocks and their connections (e.g., how the control unit connects to the motor driver).

- **Interface Definition:** Precise interfaces between components (electrical signals, data flows, mechanical connections) are defined, ensuring compatibility and reducing integration issues.

- **Viewpoints:** Different architectural viewpoints can be generated from the central model to cater to the needs of different stakeholders (e.g., electrical engineers focusing on wiring diagrams, software engineers on data flow).

4.3. Behavioural Modelling

- **Use Case Modelling:** Use Case Diagrams are used to represent how different actors (e.g., passenger, maintenance technician) interact with elevator system (e.g., "Call Elevator," "Enter Destination," "Emergency Brake Activation").

- **Activity Modelling:** Activity Diagrams model the sequence of actions and decisions within the elevator system (e.g., the process of dispatching an elevator, the sequence of operations during a floor stop).

- **State Machine Modelling:** State Machine Diagrams represent the different states an elevator or its components can be in and the transitions between them (e.g., "Idle," "Moving Up," "Moving Down," "Door Open," "Emergency Stop"). This is crucial for defining and verifying control logic and safety critical behaviour.

- **Sequence Modelling:** Sequence Diagrams illustrate the temporal order of messages exchanged between different parts of the system during a specific scenario (e.g., the interaction between the car call button, control unit, and motor when a passenger presses a button).

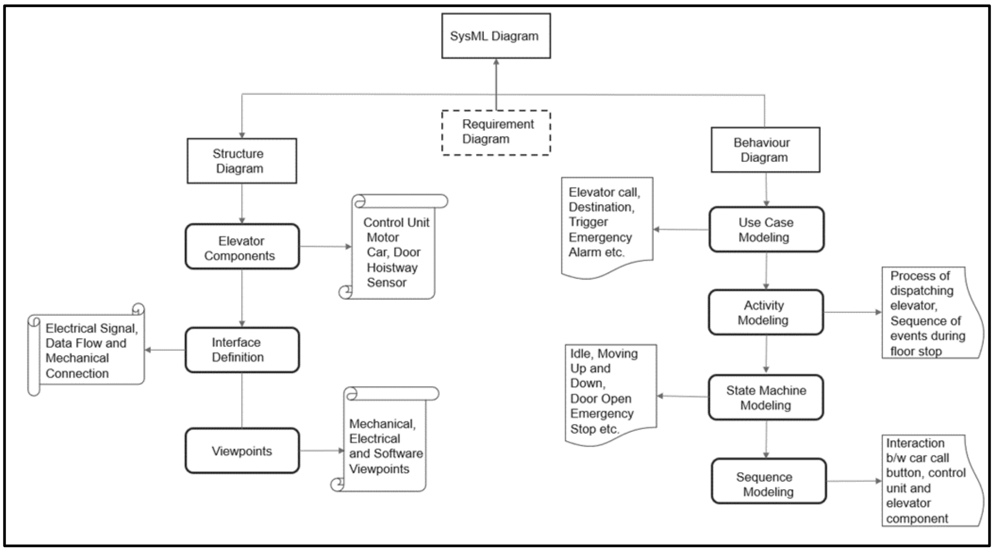

Figure 2: SysML Block Diagram for Structural and Behaviour Modelling of Elevator

4.4. Verification and Validation

The verification & Validation (V&V) model can be used completely new modern elevators starting from market requirements to the final support to field feedback as shown in Figure 3.

- **Market Requirements & Feasibility Study:** The V&V model starts with studying the market requirements and then identifying the functional requirements (e.g., speed, capacity, new innovations and advance safety features). It is followed by feasibility analysis and impact analysis of new product.

- **System Design Specification:** The next step is creating a system design specification of new elevator. It includes detailed design choices for an elevator system, derived from system architecture and architectural design. It acts as a blueprint, how the system will be built and how the component will interact to fulfil requirements.

- **Component Design Specification:** It includes details of specific design of each individual components, interface between components their functionalities and behaviour.

- **Implementation:** The mechanical, electrical and software development team and start working on system and component model into a physical and working elevators. The implementation is in adherence of component and system design specification.

- **Component Qualification:** After the system is established, verification activities confirm that design component meets the specified requirements. This stage uses simulation and analysis to verify the design performance, such as simulating elevator car movement, door operations and safety mechanism. Example of component qualification using simulation is that it can verify elevator's braking system is adequate for the specified load and speed, or door closing mechanism won't trap the passenger.

- **System Qualification:** This stage involves testing and validating actual the physical elevator system behaviour using simulations. It confirms that the integrated system functionality correctly meets all the requirements. For elevator example of system qualification can be to verify the system's ability of handle a variety of passenger loads and traffic pattern while maintaining safety (e.g., heavy traffic, power failure, emergency stops) and performance. This helps identify performance bottlenecks, safety hazards, and design flaws early in the design phase.

- **Field Data Feedback:** The feedback from field on any unexpected behaviour can be validated using model simulation validation and design change can be suggested.

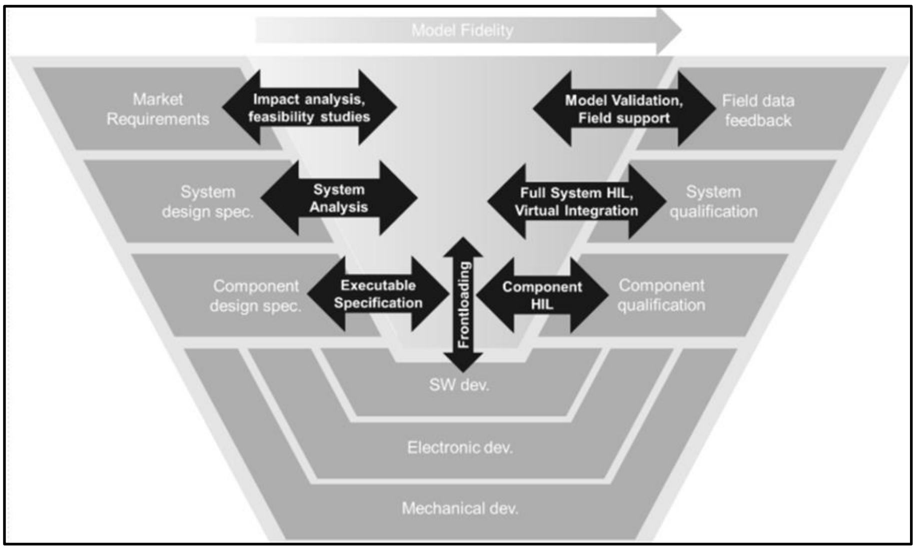

Figure 3: MBSE: Applying Verification and Validation Elevator life cycle development

MBSE emphasizes continuous V&V throughout the elevator's lifecycle, including operation and maintenance. This involves monitoring the system's performance in the field, collecting data and using the data to refine model and improve the system. This continuous process will ensure elevator system continues to meet requirements and perform reliably over time.

4.5. Use case of V&V applied to elevators

The components used in elevators are tested under different loading and testing scenario. However, when the same components are integrated with elevators its behaviour changes due to new operating condition as shown in Figure 4.

The system level qualification can be done to virtually simulate the behaviour of components integrated to full elevator system. This simulation can help to understand the component behaviour and to optimize the system behaviour.

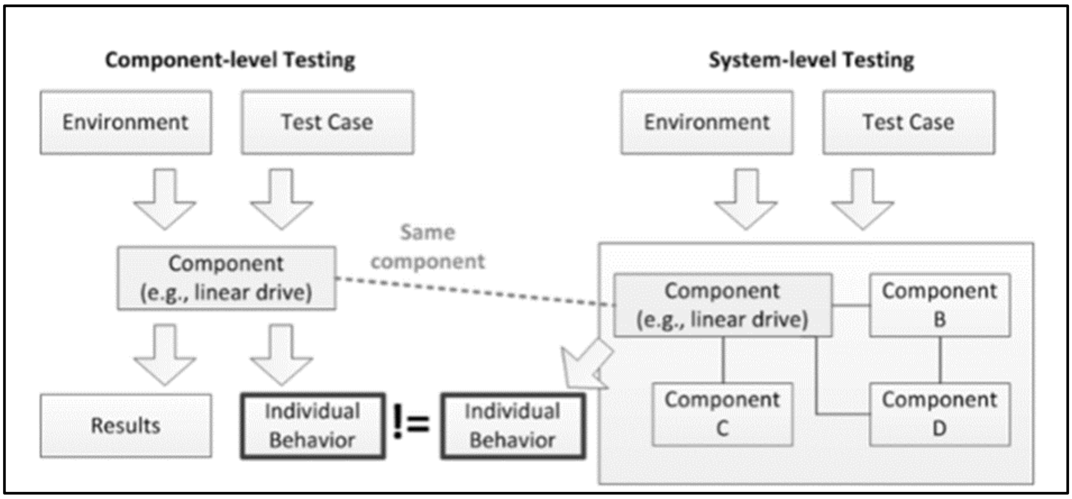

Figure 4: Individual behaviour in component level testing and system level testing

4.5. Collaboration

- **Shared Model:** MBSE enables team to collaborate on a single, unified system model, break down communication silos and fostering a shared understanding.
- **Real – time Updates:** MBSE tools provide real-time updates to the model, ensuring all stakeholders working with latest information and reducing inconsistencies.
- **Integrated Communication:** MBSE tools can integrate communication feature like chat, comments, and permissions, further enhancing communication.

4.6 Traceability

- **End-to-End Traceability:** MBSE tools allow for linking stakeholder requirements into component and system design, implementation and verification, creating traceable path throughout life cycle.
- **Visual Contextualization:** The requirements are embedded withing system models, allowing stakeholder to visualize how they influence system architectures and behaviour.
- **Dynamic Verification:** Executable MBSE models enables automated verification of requirements through simulations, catching errors in early development process.
- **Impact Analysis:** Traceability enables teams to understand the impact of requirements changes on other part of the system, facilitating efficient change management.

5. Benefits of MBSE in Elevator Systems

The adoption of MBSE offers significant advantages for elevator manufacturers and operators:

- **Improved System Quality:** By reducing ambiguity and enabling early validation, MBSE helps design more robust, reliable, and higher-performing elevator systems.
- **Reduced Development Time:** Early detection and resolution of design flaws, streamlined communication, and automated processes lead to shorter development cycles and faster time-to-market.
- **Cost Savings:** Less rework, fewer physical prototypes, and efficient change management translate into substantial cost reductions throughout the development and maintenance phases.
- **Enhanced Safety and Reliability:** Rigorous modeling of safety-critical functions and early simulation of failure modes significantly improve the intrinsic safety of elevator systems.
- **Better Communication and Collaboration:** A shared, unambiguous model fosters seamless communication across multidisciplinary teams, suppliers, and even customers, leading to better alignment.

- **Increased Innovation:** By providing a clear and comprehensive understanding of the system, engineers can explore more design alternatives and implement innovative features with greater confidence.

- **Effective Knowledge Capture and Reuse:** Models serve as a living repository of system knowledge, enabling efficient reuse of design patterns, components, and intellectual property for future projects.

- **Improved Maintainability and Evolution:** A well-documented, model-based system is easier to maintain, troubleshoot, and evolve with new features or regulatory changes.

6. Key Enablers and Tools

The successful implementation of MBSE relies on a combination of methodologies, standards, and tools:

- **Systems Modeling Language (SysML):** A general-purpose graphical modeling language used to specify, analyse, design, and verify complex systems.

- **MBSE Tools:** Software platforms that support the creation, management, and analysis of system models (e.g., Dassault Systems CATIA No Magic, Cameo Systems Modeler, IBM Engineering Systems Design Rhapsody, Sparx Systems Enterprise Architect). These tools often provide simulation, code generation, and requirements management capabilities.

- **Methodologies:** Established MBSE methodologies (e.g., Harmony-SE, OPM, Use Case Driven Approach) guide the application of modeling concepts throughout the lifecycle.

- **Organizational Change Management:** A commitment from leadership and a cultural shift within the organization are crucial for successful MBSE adoption, including training and new roles.

7. Case Study: Redesigning an Elevator Control System with MBSE

Consider an elevator manufacturer aiming to develop a new generation of smart, connected elevator control systems with advanced predictive maintenance capabilities and dynamic dispatch algorithms.

Traditional Approach:

1. Different team work separately on hardware, software, and safety specifications.
2. Software development proceeds based on textual requirements.
3. Hardware prototypes are built.
4. Integration testing reveals mismatches between hardware capabilities and software demands.
5. Safety requirements are validated late in the process, requiring extensive physical testing.
6. Changes to dispatch algorithms necessitate manual updates across multiple documents and re-testing.

MBSE Approach:

1. **Requirements Modeling:** All functional, performance, and safety requirements are captured in a SysML requirements diagram, linked to stakeholders and use cases.

2. **Architectural Modeling:** The control system's architecture is modeled using BDDs and IBDs, defining components like the main controller, motor driver, sensor array, communication module, and HMI. Interfaces (e.g., CAN bus, Ethernet) are precisely defined.

3. **Behavioral Modeling:**

    - **State Machines:** Model the lifecycle of the elevator car (e.g., Idle, Moving, Door Open, Emergency Brake).

    - **Activity Diagrams:** Model the passenger request handling logic, dispatching algorithms, and maintenance routines.

    - **Sequence Diagrams:** Illustrate the precise communication flow for predictive maintenance data collection from sensors to the control unit and then to a cloud platform.

4. **Simulation & Analysis:**

    - The behavioral models are simulated to test dispatching efficiency under varying traffic loads.

    - Safety-critical state transitions are analysed to ensure adherence to safety standards (e.g., fail-safe mechanisms for door interlocks).
    - Performance simulations predict energy consumption for different operational profiles.

5. **Traceability & Validation:** Every line of generated software code and every hardware component is traceable back to a specific requirement in the model. Model-based testing generates comprehensive test cases, ensuring thorough validation.

6. **Collaboration:** Mechanical, electrical, and software engineers collaborate on the shared model, understanding each other's constraints and design choices in real-time, leading to faster issue resolution.

Outcome: The MBSE approach leads to a more robust, optimized, and safer elevator control system. Design flaws are caught in the modeling phase, reducing rework during integration. The time-to-market is significantly reduced, and the system is easier to adapt to future smart building features.

8. Challenges and Considerations for Adoption

While the benefits of MBSE are compelling, its adoption is not without challenges:

- **Initial Investment:** Significant upfront investment in tools, training, and establishing new processes.
- **Cultural Shift:** Moving from a document-centric to a model-centric mindset requires a substantial cultural shift within engineering teams.
- **Tooling Integration:** Ensuring interoperability between MBSE tools and other engineering tools (CAD, FEA, software IDEs) can be complex.

- **Expertise Gap:** A shortage of experienced MBSE practitioners and modelers.
- **Model Complexity:** Overly complex models can become difficult to manage if not designed and governed properly.
- **Legacy Systems:** Integrating MBSE with existing legacy systems and processes can be a gradual and challenging endeavour.

Successful adoption requires strong leadership, a phased implementation strategy, comprehensive training, and a clear vision for how MBSE will integrate into the existing engineering ecosystem.

9. Conclusion

The vertical transportation industry is on the cusp of a technological revolution, driven by smart building initiatives, IoT, and increasing demands for efficiency and safety. Traditional engineering approaches, while foundational, are becoming increasingly inadequate to address the escalating complexity of modern elevator systems.

Model-Based Systems Engineering offers a powerful and comprehensive solution to reimagine vertical transportation development. By embracing models as the central artifact, elevator manufacturers can achieve unparalleled clarity, precision, and collaboration across their engineering disciplines. The promise of MBSE – faster development cycles, reduced costs, enhanced safety, and superior product quality – positions it as an indispensable methodology for designing the next generation of intelligent, reliable, and sustainable elevator systems. Adopting MBSE is not merely an engineering choice; it is a strategic imperative for companies seeking to lead in the future of vertical mobility.

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BIOGRAPHICAL DETAILS

Upendra Kumar Singh, an IIT Guwahati M. Tech alumnus, brings over 14 years of expertise in Virtual Validation Technologies, MBSE, and FEA. He's currently a Principal Engineer at Schindler India Pvt. Ltd., where he leads System Simulation.

AMRUT INGALE is a highly experienced professional with 18 years of industrial expertise in the design and development of material handling equipment and elevators. He holds a master's degree in mechanical design from Pune University. Currently, he is contributing his skills in a System Engineering role at Schindler India Pvt. Ltd.