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Teaching conceptual modeling at multiple system levels using multiple views

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Abstract

Conceptual models are models that support understanding and reasoning about problem and solution space by abstracting in many directions. Experienced lead designers and architects collect a rich set of such models including figures of merit over time. In many cases, the conceptual modeling is a tacit competence. We have transformed this way of working in the area of designing semiconductor equipment into an educational module. In several workshops, we have seen the application of similar modeling in other domains. The essence is that conceptual models are made at multiple levels, e.g. for elementary components, their functionality and properties, aggregated modules or subsystems, the entire system, the system in its operational context, and the impact on the customer's business. At every level, multiple views are needed to understand and reason. Typical views include physical models, functional or dynamic behavior models, and performance models in mathematical and quantitative form. This paper describes how we teach conceptual modeling to master students and how the chosen format and case helps in achieving the learning outcome.

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Conceptual modeling; performance; visualization; education

1. Introduction

System designers model conceptually to understand, reason, communicate, and make decisions regarding problem and solution space. Conceptual models, see [1, 2, 3], are models that by simplification model at a high level of abstraction. These models are a combination of visualizations (e.g. diagrams, timelines, graphs, and sketches), mathematical formulas, and quantitative calculations.

We have developed an educational case based on elevators to teach conceptual modeling. The elevator case is sufficiently complex to appreciate modeling, while it is sufficiently simple that all students can engage without preparation. It serves as educational case in modeling courses taught at Buskerud University College (BUC) in Norway and TNO-ESI in the Netherlands. The students have varying backgrounds:

- Many of the students at BUC have limited experience in an industrial engineering job, e.g. 1 to 2 years
- Both TNO-ESI and the remaining BUC students have significant industrial engineering experience
- All students have at least a bachelor degree in engineering or science.

These modeling courses follow a bottom-up approach to connect with the mental world of the students. The idea is that the students are well trained in the design of elementary mechanical problems, such as dimensioning of acceleration and velocity, motion control, power, thermal and structural analysis, etc. We observe that students find it challenging to increase the scope to more heterogeneous problems, such as handling input and output. We therefore guide them step-by-step from a well-defined known kinematic problem to more ill-defined problems of logistics and handling.

A core concept in architecting is a view, as defined in ISO/IEC 42010:2011, as the perspective that is defined by a stakeholder in combination with a concern. The standard

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explains that a view can be captured in a model, so that the models together can describe an architecture.

1.1. Educational objectives

The educational goal of the case is to show several modeling aspects to make the students aware of them:

- The need for various views, e.g. physical, functional, performance; see [4, 5]
- The need for mathematical models
- The need for quantified understanding
- The need to make assumptions, when input data is unavailable yet, and the need for later validation
- The need for various visualizations, e.g. graphs
- The need to understand and hence model at multiple levels of abstraction
- The need to start simple and to expand in detail, views, and solutions gradually, based on increased insight
- The value and the limitations of these conceptual models
- The complementarity of conceptual models to other forms of modeling, e.g. problem specific models (e.g. structural or thermal analysis), SysML models, or simulations

On top of the awareness, an educational objective is to help students over the threshold of making assumptions and estimates. For several reasons, we observe that students hesitate to make assumptions. For example, they fear that the assumption is invalid and hence their result wrong. or, when they have worked in practice, they may have experienced that results are taken for valid, despite uncertainty in the input data. The purpose is to help them break out of the vicious circle of lack of insight and understanding, what blocks them to gather input data, which in turn blocks them for gaining insights and understanding by conceptual modeling.

At an higher level of competence, we strive to teach them that “framing the problem” and “exploring the solution space broadly” are essential systems engineering steps.

1.2. Educational format

The educational model is to guide the students through the case, where the students are continuously challenged to actively, step-by-step, model. After every step, teacher and students briefly reflect on results and the method used in that step.

1.3. Basis of the case

The basis of the case stems from our experience in developing wafer scanners. We observed systems engineers of wafer scanners during the systems design phase. Wafer scanners are systems that expose semiconductor wafers with high resolution (tens of nanometers) patterns with a high throughput (more than 100 wafers per hour). The throughput is realized by a combination of fast movements and high exposure intensity.

One of the key performance parameters of wafer scanners is throughput. The mechanical design dominates throughput design. Since wafer scanners are complex machines, we have transposed the experiences in wafer scanners into elevators, which have similar mechanical design considerations in a less complex machine.

2. The elevator case

Figure 1 shows how the teacher initially introduces the case (The course material can be found at http://www.gaudisite.nl/ElevatorPhysicalModelSlides.pdf). We have a building of 40 meters high, with an elevator. Main stakeholders are the inhabitants that want to reach their destination fast and comfortable and building owner and service operator who are concerned about economic constraints related to space, cost, and energy.

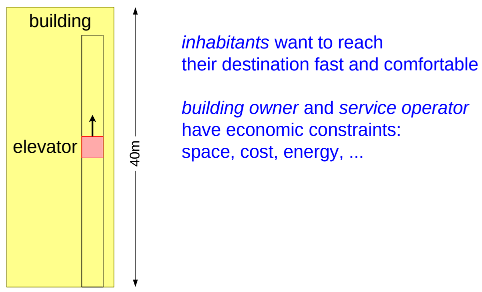

Fig. 1. Initial case introduction.

Next, the teacher quickly refreshes the kinematics formulas; see Fig. 2. These formulas are the trigger for the first student activity. The students have to make an estimate of the values for the maximum velocity, acceleration, and jerk, and an estimate of the time needed to reach the top floor (without stopping at any of the intermediate floors). This question forces the students to reason about numbers based on their experience, since they do not have any source of information.

S_t = position at time t

v_t = velocity at time t

a_t = acceleration at time t

j_t = jerk at time t

$$v = \frac{dS}{dt} \qquad a = \frac{dv}{dt} \qquad j = \frac{da}{dt}$$

Position in case of uniform acceleration:

$$S_t = S_0 + v_0 t + \frac{1}{2} a_0 t^2$$

Fig 2. Refresh of (mostly secondary school) kinematics

The results from the students typically are reasonable. The teacher now presents some number from an Internet source: v_{max} ~= 2.5 m/s, a_{max} = ~1.2 m/s^2, j_{max} ~= 2.5 m/s^3, and $t_{top\ floor}$ ~= 16s. These numbers are inputs to the first modeling exercise: *Make a model for $t_{top\ floor}$, make a 0th order model with constant velocity and a 1st order model with constant acceleration. What do you conclude from these models?*

Fig. 3 shows the 0th order model and Fig 4 the first order model. Both figures show schematic graphs to show position S, velocity v, and acceleration a as function of time. Below the graphs, the mathematical models for these same variables with the main parameters are shown, and the right hand side shows the quantification.

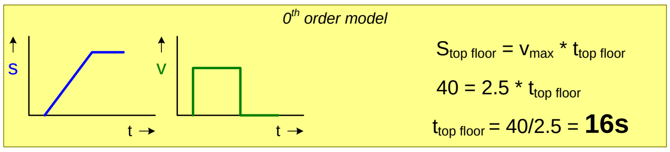

Fig 3. 0^{th} order model to move to the top floor

The schematic graphs help to understand the concepts of the model, and the variables that are used. The mathematical formulas facilitate calculations and reasoning. The quantifications help us to achieve concrete results. When we look at the contributions to the total time , then we see that for these values, the time traveling with maximum velocity is dominating. This allows us to lift the formula one abstraction step into $t_{top\ floor}$ ~= S/v_{max} + (t_a+t_j); the velocity determines the time plus a small correction for acceleration and jerk.

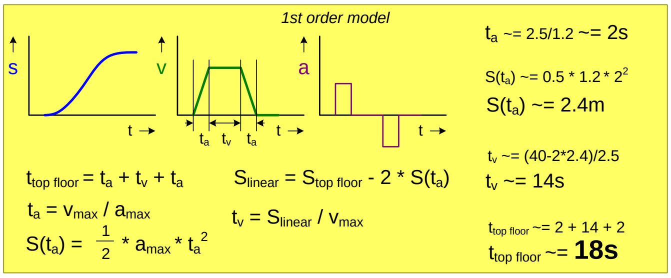

Fig 4. 1^{st} order model to move to the top floor

At this point the teacher broadens the scope and asks for a model for $t_{top\ floor}$ that takes docking of the elevator and doors into account. Fig. 5 shows a functional model at the left hand side, a performance model as mathematical formula at the top, and the quantification at the bottom. The functional model is a model that describes the dynamic behavior and forms the basis for the performance formula. Once more, the students have to make assumptions for missing data. In this case, docking and door performance is unavailable, so estimates of a few seconds per action are used. Based on these numbers, we conclude that the traveling time is dominating, however, the docking and door-handling time is significant. We can lift the $t_{top\ floor}$ formula one level, by writing it as $t_{top\ floor} = t_{travel} + t_{elevator\ overhead}$.

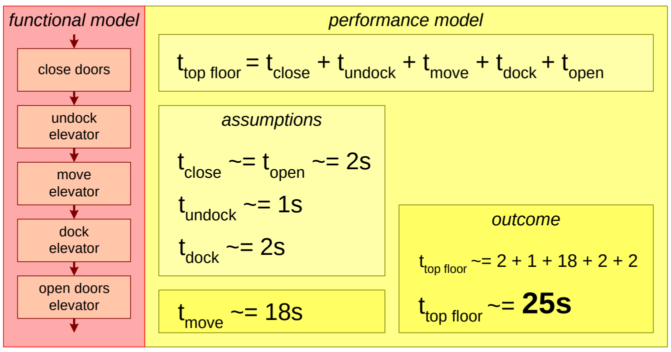

Fig. 5 Model including docking and doors

As intermezzo, the teacher now briefly discusses the degree of simplification used in the current models, by showing the Internet data that provides initial values for v, a, and j; see Fig. 6. The graph in Figure 6 shows the measured acceleration of an elevator as function of time. From this graph, we can easily see an upward acceleration of 1.2 m/s^2, while the slopes of the acceleration determine the jerk. We can also see the docking and undocking time, where the acceleration is non-zero before acceleration and after deceleration. Lastly, we see that during the entire movement of the elevator, the acceleration is varying slightly. These variations are due to mechanical effects (slack, elasticity, damping) and control effects. A kinematic model abstracts from all these variations and approximates reality by nice constant accelerations or jerks.

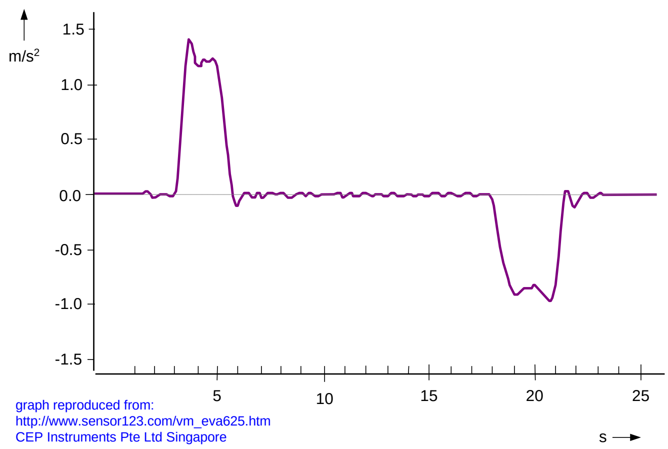

Fig. 6 Internet data used to find initial values for v, a, and j

At this point, the teacher shifts the attention back to relative small moves, from one floor to the next. Fig. 7 shows results similar to Fig. 4, a 1^{st} order model of $t_{one\ floor}$. Fig. 8 shows a 2^{nd} order approximation for the jerk time.

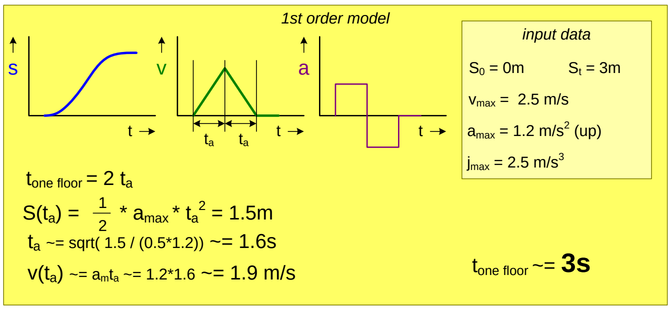

Fig. 7 1^{st} order model for $t_{one\ floor}$

For these small moves, the acceleration dominates the traveling time. The 2^{nd} order approximation shows that the contribution of the jerk is significant too: 1s on top of 3s. However, when we add the docking and door handling time, then we see that these times dominate over the traveling time: 7s of overhead on top of 4s traveling.

The students have now explored the technical properties of the elevator reasonably. The teacher broadens the case once more, by adding people who enter and leave the elevator for the same two use cases. This addition introduces concurrency in the models; the elevator and the people act concurrently, where they synchronize when entering the elevator. The teacher recommends to make a timeline to visualize the concurrency.

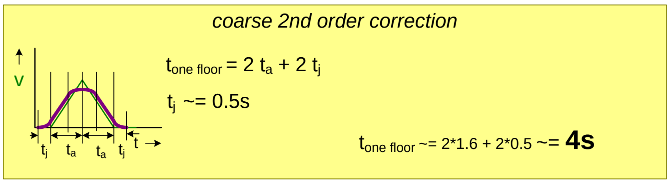

Fig. 8 2nd order approximation for $t_{one\ floor}$.

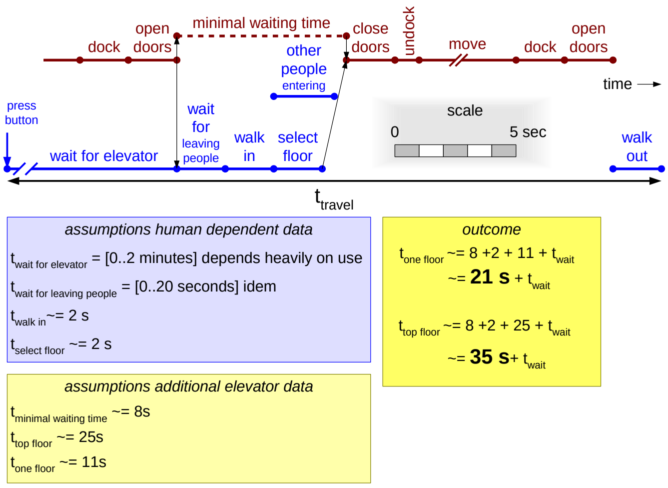

Fig. 9. Timeline of people and elevator plus time estimate.

Fig. 9 shows the timeline on top with separate lines for elevator and people. Again, we need to make assumptions to be able to estimate a total time. The model becomes less deterministic, since context dependencies cause variations. In particular, the waiting time for the elevator is context dependent. We can see that the human activities have a significant impact. Fig. 10 shows a breakdown of the end-to-end time in the various contributions.

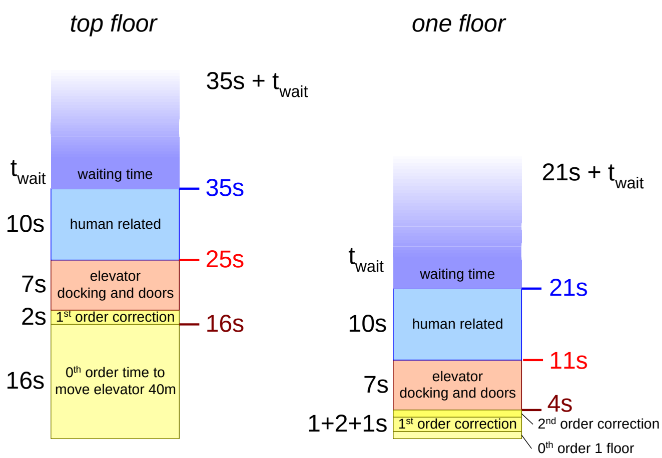

Fig. 10. Breakdown of the end-to-end time.

Figure 10 shows clearly that the context-dependent waiting time can be dominating. The other contributions, human related, elevator overhead, and kinematic properties have similar values. A high-level formula for the end-to-end time is $t_{end\text{-}to\text{-}end} = t_{human\ related} + t_{wait} + t_{elevator\ overhed} + t_{moving}$.

As side step the teacher shows that similar models can be made, at secondary school level math and physics, to estimate power and energy. A brainstorm with the students shows that many more properties can be explored, such as safety, acoustic noise, airflow, mechanical vibrations, operating life, and maintenance needs. Many of these aspects relate to the kinematic variables. For example, wear has a relation to jerk and acceleration.

After these side steps, we broaden the scope once more by going from a single group of people to multiple people entering and leaving the elevator. For example, what is the end-to-end time to travel to the top floor when at least one person leaves the elevator at every floor? The resulting model looks similar to Fig. 9, however we now repeat the sequence of moving, elevator overhead, and human related activities for every floor.

The total time to reach the top floor, with these assumptions, is large: 4 ½ minutes + waiting time. At this moment the students get another set of questions that they do not find easy to answer: What is the desired end-to-end time to get to the top floor? And what is an acceptable waiting time? Typical answers are one minute for traveling to the top floor and for the waiting time. These answers are the preparation for another change in perspective by asking: What are potential solutions to achieve this? What are the main parameters of the solution space?

The solution space includes adding elevators, applying scheduling strategies, specializing elevators in relation to their usage, and for each individual elevator the previous design parameters (kinematics, overhead) may be varied. This increase of the solution space changes the problem and modeling paradigm from straightforward kinematic and performance modeling into the logistics and scheduling domain. In this domain, we do not get a single answer; rather we get distributions and probabilities.

This logistics world is less certain and may have hidden surprises in the form of unknowns. To increase awareness of unknowns and unforeseen issues, we do a brainstorm of more exceptional use cases, resulting in cases such as non-functioning elevator, maintenance and cleaning of elevator, elevator used to move furniture, rush hour, special events (party, or new year’s eve), special floors (e.g. a restaurant at the top floor), elderly or handicapped people, and playing children. All these cases affect traveling and waiting time.

3. Educational experiences

We have been teaching this course yearly since 2007 and in between, we have used the module many times in in-house courses with more experienced engineers. Most students enjoy this module. Many of them need some time to refresh their secondary school knowledge and skills in mathematics and physics. The teacher has to encourage students to “dive in”, and really make assumptions and do the calculations.

The teacher illustrates **the need for various views,** e.g. physical view (Fig. 1), functional (Fig. 5.), performance (Fig.

4, 5, 7, and 8), and concurrency (Fig. 9). We observe that most students during the steps typically limit themselves to one or two views. Is the example sufficient for them to apply this in practice?

Most students implicitly understand the **need for mathematical models**. The risk is that the formula is too much an intermediate result that students forget soon after use.

The teacher illustrates **the need for quantified understanding** and **the need for assumptions** in every step**.** Once over the threshold, most students experience that their “best guess” is sufficient to model and gain insight. The distribution of values tends to be limited, e.g. a v_{max} between 1 and 4 m/s.

The discussion of every step illustrates **the need for various visualizations, e.g. graphs** (Fig. 3, 4, 6, 7, 8), proportional timelines (Fig. 9) or bars (Fig. 10). However, we see here the same effect as the use of views. Is the example sufficient for them to use graphs when needed?

The whole exercise is designed to show **the need to understand and hence model at multiple levels of abstraction**. We pass the following levels in the exercise: kinematic, elevator overhead, human activities, human dynamics, people logistics, and multi-elevator solutions. Again the question is whether a single example is sufficient to apply multiple levels in other situations.

The exercise shows that a **simple start and gradual expansion in detail, views, and solutions** is effective. Every step in the process increases the level of understanding and insight. In this relative simple case, we do not yet reach an essential question in conceptual modeling: “When to stop modeling?”

In about 2 hours, the students experience the **value and limitations of the models**. At the end, they have explicit insight in elevator performance and the solution space. They experience that despite many assumptions, meaningful insights are achieved. Their experience helps them to realize that the numbers may not be representative. However, the exercise helps them to search for needed inputs.

The teacher helps to conclude by reflection that **framing the problem** and **exploring the solution space broadly** as competence is essential. It is difficult to assess whether we have achieved to develop this competence.

Most students enter the course with specific expectations. For example, we expose the students early to SysML, where many of them implicitly equate modeling and using SysML. We observe that students with other backgrounds sometimes have similar limited views on modeling. Most students acknowledge at the end of the exercise that the example is enlightening. We conclude from that feedback that they are now aware of the **complementarity** of conceptual modeling in relation to other forms of modeling.

4. Application of this type of modeling in practice

While facilitating architecture workshops and architecture assessments, we encountered a few times problems that architects addressed with similar conceptual modeling approaches.

For instance in analysis and instrumentation equipment, the materials handling shows many similarities with the elevator case. In most cases, architects and designers understand the mechanical design (determining the kinematic behavior) is well leaving little room for improvement. However, the in-system overheads and the material logistics often lack ownership, which results in uncontrolled emergence. Conceptual modeling in a workshop quickly creates a common understanding between architects and designers of potential issues. The common understanding helps participants to reframe their problem, and hence to focus on the most promising improvement opportunities.

Students modeling deployment of defense and subsea oil and gas equipment discover that their core systems have limited room for further improvement. However, they discover that more significant improvements are possible in the immediate context, for instance in deployment of the systems.

During a recent architecture assessment of a goods flow system, we encountered similar models as shown here, with very similar problems and trade-offs.

We conclude from these spontaneous applications in practice that this type of conceptual modeling is a “best practice”.

5. Conclusions

We guide the students in two hours through a case applying conceptual modeling where we illustrate many aspects of conceptual modeling, e.g. multiple views, mathematical models, quantification, assumptions, visualizations, multiple abstraction levels, and the value and limitations of models. We strive for an improvement in their competence of framing the problem and exploring the solution space broadly. After the case, students typically are aware of the complementarity of conceptual models to other types of models, such as SysML and simulations.

6. Future Research

The main assumption behind the education and this paper is that conceptual modeling is an effective approach for systems design. This assumption needs validation. Davies et al [3] observe that conceptual modeling in practice is not easy and hence often not applied. This immediately raises next questions:

- Is the training module effective in creating awareness for all described aspects?
- What additional training do we need to teach to achieve a level of competency that students can apply conceptual modeling in practice?

Acknowledgements

The participants of the modeling courses have provided feedback and insight to the elevator case.

References

[1] Robinson S., Conceptual Modelling: Who Needs It? SCS M&S Magazine 2010 / n2 (April) http://www.scs.org/magazines/2010-04/index_file/Files/Robinson.pdf

[2] J. Sokolowski, C. Banks, Modeling and Simulation Fundamentals: Theoretical Underpinnings and Practical Domains, Wiley (2010)

[3] Davies I., Green P., Rosemann M., Indulska M., and Gallo S. How do practitioners use conceptual modeling in practice? Data Knowledge and Engineering July 2005.

[4] Bonnema, G.M., FunKey Architecting - An Integrated Approach to System Architecting Using Functions, Key Drivers and System Budgets, PhD thesis University of Twente, 2008

[5] Borches, D. A3 architecture overviews: a tool for effective communication in product evolution, PhD thesis University of Twente, 2010