Maplesoft specializes in the modeling, simulation, and optimization of complex multidomain systems in the manufacturing and industrial automation industries. Modeling the mechanical, electrical, hydraulic, and control systems of your equipment within a single environment provides insight into the complex interactions between the systems. By performing system-level design and analysis, you can identify problem areas early in the design cycle. Maplesoft Engineering Solutions provide you with the expertise and tools you need to reduce development risk and bring high-quality products to market faster.

This article illustrates how engineers involved in the design of complex machines are making significant strides in their work with the help of the Maplesoft Engineering Solutions team. Learn more about such diverse projects as revolutionary mining equipment, more reliable offshore machines, a parametric approach to designing an industrial pick-and-place robot, and improved performance of crane control systems.
In the mining industry, processing plants are generally constructed on the site of extraction. Mined ore gets transported by super-heavy duty trucks to the plant, where it gets crushed into smaller sizes before being stockpiled, or transported offsite for further processing. Besides the ore, the mine typically has to move four times as much overburden as ore. Big mines typically have to move 700,000 tonne of material per day. As the mine gets larger, the trucks have to travel longer distances to deposit their load, resulting in significant increases in the cost of fuel and vehicle maintenance.

To address this problem, FLSmidth engaged the services of the Maplesoft Engineering Solutions team to develop design and analysis tools that would help them design a Dual Truck Mobile Sizer (DTMS) - an innovative machine that can be relocated throughout a project, as the haul distances increase.

The DTMS increases in-pit crushing efficiency due to its dual-skip configuration. A truck backs into one skip until it reaches a restraining curb in the floor. After dumping its load on the skip floor, it then slowly pulls ahead, lowers its bed, and pulls away. Once the truck clears the end of the skip, the skip can be raised. As the skip is elevated, it pours material from the discharge of the skip and deposits the material into the apron feeder hopper. As material is introduced onto the apron feeder, it conveys the material to the sizer where it is crushed to the appropriate size. After being crushed, the material is deposited onto the discharge conveyor where it is taken to the bench conveyor. This process is performed while another haul truck is depositing material into the twin skip, thereby increasing the number of truck cycles.

To create tools that would help FLSmidth to design this innovative piece of equipment, the Maplesoft team first had to develop a deep understanding of the dynamics of the skip system. They began by using MapleSim, the advanced modeling and simulation platform, to develop a fully parameterized model of the skip. Taking advantage of MapleSim’s multidomain modeling capabilities, they were able to create a high-fidelity model that incorporated all the key components of the skip - from its geometric structure and mechanical operation, to the hydraulic circuits and controllers.

“The DTMS is a very large and complex machine,” says Willem Fourie, Global Product Line Manager - Mobile Sizer Stations, FLSmidth. “The ability to model all aspects of its operation during the design phase using MapleSim gave us confidence that the product we would ultimately build would function correctly the first time. We cannot even begin to put a value on what this means to us.”

MapleSim’s modeling approach not only addresses the basic requirements of dynamic multidomain simulation, but through seamless access to the underlying symbolic equations, enables the user to rapidly create targeted design tools using Maple’s high-performance symbolic computation engine.
The creation of the skip model was complemented with the development of multiple design tools to aid in adjusting the model to achieve the desired behavior. One such design tool is the Geometric Design Evaluation tool, which provides the ability to evaluate changes in the dimensions of the skip design and their effect on the dynamics of the system. The tool uses Maple, Maplesoft’s symbolic computation tool, to perform a parameter sweep, by simultaneously running simulations using the different parameter values provided. Maple then presents the results overlaid on a single plot window for easy comparison and evaluation. Other tools developed include tools for sizing the hydraulics and components, designing the motion profile, investigating the dynamic loading on the bearings, and estimating the material flow load.

As part of developing and testing the skip model, Maplesoft’s technical team also evaluated the design, to identify the sources of vibrations and their effects. They developed an approach to perform stability analysis, which was made possible by the fact that the skip model provided easy access to key geometric features and dynamic properties of the design. The stability analysis approach was demonstrated using a case study in which the location of the feedback sensor was varied. The analysis identified a potential issue very early in the design phase, enabling engineers at FLSmidth to develop a more robust design.

“The stability analysis performed by the Maplesoft team was very insightful,” said Fourie. “Knowing about a potential issue early on enabled us to design with it in mind, rather than having to go back and rework our design at a later stage. This contributed to keeping our project on track, and saved us millions of dollars down the line.” The stability analysis design approach and all the other analysis tools developed by Maplesoft were delivered to FLSmidth, enabling them to apply them to future projects.

Once the modeling and testing of the skip system was completed, during the following phases of the project, Maplesoft staff went on to develop the chassis model, and finally the full DTMS. Many more design tools were created, providing the ability to evaluate joint flexibility, center of mass variations as the skip was raised and lowered, and even soil modeling to investigate the vertical displacement of the system on different types of soil.

"From start to finish, Maplesoft provided truly knowledgeable and professional service," concludes Fourie. "Their team worked tirelessly to accommodate our schedule, and the power of the Maplesoft toolset is second to none. The level of design detail and the amount of insight we gained have enabled us to revolutionize onsite crushing through the development of the DTMS. We could not have achieved this without the services the Maplesoft Engineering Solutions team."

Full DTMS model, including footings and soil interactions
A Parametric Approach to Designing an Industrial Pick-and-Place Robot

Industrial automation is on the rise, with machines performing more and more tasks every day. Designing these complex industrial machines is a challenging process. Engineers need to ensure that the machine they design meets many different performance objectives, for productivity, workspace, maneuverability, payload, and so on. But at the same time, they also need to develop a design that will minimize both production and maintenance costs, such as using the smallest possible motors and the shortest links for robot arms, and minimizing loading to reduce the wear and tear that leads to expensive repairs and downtime. All these requirements must be taken into account when developing an industrial machine to ensure a high-performing product at the lowest possible cost.

A leading provider of packaging machines approached the Maplesoft Engineering Solutions team in the early stages of the design of a new product that incorporates a pick-and-place robot. They turned to Maplesoft to help them answer questions about the design of their new product, including:

- What is the proper motor sizing for the robot?
- What lengths should the links be to achieve the desired workspace?
- What effect will different combinations of link lengths have on the design?
- What will the required performance from the motor and gearbox be?

The Maplesoft Engineering Solutions team applied a parametric physical modeling approach to answer these questions. They used MapleSim, the multidomain system-level modeling and simulation platform, to develop a high-fidelity parameterized model of the desired robot type. Then they used the advanced computation capabilities of Maple to develop analysis tools that examine the operation of the system and its dynamic behavior with different sets of parameter values. These analysis tools, together with the high-fidelity model, provided the client with the insight required to determine how to optimize their design, and provided them with a toolset they could easily configure for use in the design of similar products.

An example of a typical pick-and-place robot is shown in Figure 1. The robot model is mounted on a reference base, to which three links that form the robot arm are connected. The links are actuated by three servo motors, which provide the rotational motion and control with three degrees of freedom. The end effector consists of a translational component attached to the third link, allowing for the desired pick-and-place action.

![Figure 1. Design of a 3-link pick-and-place robot arm in MapleSim.](image)

Each of the link structures includes sensor components to provide force and torque information, which can later be used to determine radial force, axial force, and bending moment at each bearing. The model also includes numerous probes embedded at strategic locations within the design, to monitor performance characteristics such as required motor speed and torque, along with joint angle and constraints.

Initial simulations were run in MapleSim, to observe the behavior of the system, with the probe information presented in various plots. The model was then loaded into Maple for in-depth analysis.
The Maplesoft Engineering Solutions team created a set of analysis tools in Maple, to provide the client with insight into different areas of their design that will help them make design decisions for the final product. Taking advantage of the fully parametric nature of the high-fidelity model developed using MapleSim, and Maple’s symbolic computation engine, the tools enable the client to perform multiple iterations of simulations, to determine the best combinations of parameters.

The first design tool developed by Maplesoft enabled the client to perform kinematic analysis. The kinematic analysis allowed them to check the robot’s workspace, visualize its motion, and determine any path offsets if required. The robot motion is affected by whether the robot’s elbow is configured to be on the right side or the left side. One of the features of the kinematic analysis tool was to perform the inverse kinematics calculations, and evaluate for both elbow positions. By observing its behavior in both cases, the client was able to make an informed decision about which side to place the elbow – a decision which was then carried forward and applied to all further analyses.

The next step was to determine whether the robot was operating within the range of allowable motion, and whether any of the joint angles were exceeding the desired limit.

For each joint, multiple variables including joint angle, angular velocity, and angular acceleration were determined, based on the desired path of the end effector motion. The results showed that the initial end effector design path resulted in large angular acceleration spikes, indicating that the client needed to make some modifications in order to smooth out the motion used to actuate the joints. The adjustment would not only decrease the magnitude of the acceleration spikes, but would also result in reduced joint load, and reduced motor and bearing operating requirements.

While the client naturally wanted to use the smallest motors possible, they also had to ensure that the motors they selected would still meet the robot’s performance goals. The Maplesoft Engineering Solutions team developed an analysis tool to assist the client with motor sizing. The speed, torque, and energy of the motors were determined and plotted, then overlaid on the manufacturer’s performance curves for the targeted motors. The motor performance curves were selected from a list of possible motor data imported into Maple. For each of the motors, the client could then compare simulated results with data for different motors from the manufacturer’s specifications. Using the analysis tool, the client was able to consider different motor configurations capable of performing within the desired range. A similar approach of overlaying the manufacturer’s data on simulated data was taken to explore the gearbox limits and the selection of different gear ratios.

Another analysis tool developed by Maplesoft was a parameter sweep to observe the effects of different link lengths on the operation of the robot. Simulating the model with different link length configurations within a pre-determined permissible range enabled the client to observe the corresponding effects on performance characteristics such as motor speed, torque, load requirements, and workspace variations. Maple automatically makes use of parallel processing, allowing the user’s computer to simultaneously run multiple simulations using different parameter values, and then presents the results overlaid in a visualization window for quick and easy comparison.
Using these, and numerous other tools developed by the Maplesoft Engineering Solutions team, the client was able to apply a comprehensive approach to analyzing their design decisions, and arrived at an ideal design for their industrial pick-and-place robot.

The Maplesoft Engineering Solutions team developed a highly configurable solution that helped the client address the challenges they were facing when designing industrial pick-and-place robots. Developing a fully parametric system model in MapleSim provided access to all the system parameters required to analyze and optimize the behavior of the system. Maple’s symbolic computation engine enabled the development of a wealth of analysis tools that explored the relationships between system parameters, and their effects on the overall performance. This parametric approach meant that not only was the packaging company able to make informed design choices and arrive at the optimum configuration for their targeted application, but that they could reuse the same tools in other contexts. By modifying the parameters, they can use the same model and analysis tools to optimize and validate the designs of other pick-and-place robot products they develop in the future.

Figure 3. Example parameter sweep results for varying link lengths.
A Norwegian university research project in partnership with Aker Solutions is using MapleSim models to predict the performance of complex offshore materials handling equipment. In the short term, the work is helping designers pick the best components for the job. Ultimately, it aims to automate more of the design process.

With offshore oil and gas drilling rigs costing millions of dollars a day, their crews need to ensure they get the job done as quickly as possible. That job involves assembling the thousands of meters of flexible pipe that make up a drill string, and doing so safely and consistently on a remote platform where space is at a premium and weather conditions are frequently challenging.

Modern drilling platforms make use of highly specialised materials handling equipment to ensure components are moved quickly, precisely and safely to keep the rig on schedule. Typically, this equipment is hydraulically operated, with most modern systems also incorporating a sophisticated electronic control system, which simplifies operation and permits a considerable degree of automation.

Designing such control systems is challenging because when a crane is in motion its dynamic behavior depends upon, among other things, the precise electrical and hydraulic behavior of the control valves, the performance of its hydraulic actuators, the inertia of the crane’s structure, its load and the complex interactions between all these components.

This complexity not only makes programming a crane’s control system difficult, it also raises challenges for its mechanical and hydraulic design. Design teams must ensure that the hydraulic components they pick will deliver the required level of responsiveness, or ‘bandwidth’, while also considering a host of other factors including the cost, size and weight of components, their long term reliability, and ease of maintenance.

An ongoing research project at the Department of Engineering of the University of Agder in Norway, carried out in conjunction with offshore equipment maker Aker Solutions, aims to simplify this formidable design challenge by allowing engineers to build and run detailed simulations of equipment before they assemble a single part. MapleSim, the system-level modeling tool from Maplesoft, is playing a critical role in this initiative.

Morten Kollerup Bak is the PhD research fellow in charge of the project. He explains how it is done. “Our aim is to use model-based design to predict the behavior of the finished products and to support key design decisions,” he says. “For that to work, everything depends on your being able to model the entire structure and control system in sufficient detail to get a realistic idea of its performance.”

In Bak’s work, MapleSim is vital for the construction of such accurate models. “I divide the whole system into three different models - the mechanical structure, the hydraulic actuation system and the electrical control system,” he says. “I’m using MapleSim to model the first two parts and in some cases all three.”

MapleSim is good for this work, he explains, because it combines an extensive library of standard elements with the ability to easily integrate custom parts. And this degree of customization is essential to achieve the accuracy and detail required for model-based design.
“Our aim with this work is to build the models of hydraulics as much as possible from standard catalogue data,” notes Bak. “But we quickly found that component manufacturers don’t always provide all the data you need, particularly when you are looking at the precise behavior of their components in dynamic conditions.”

To obtain the missing data, Bak has built custom models of key components, like control valves, and validated their accuracy by conducting tests on single components operating in isolation.

Once he has confidence in the performance of the custom elements, Bak can integrate them into the MapleSim models of the entire actuation system and then use that to evaluate the likely performance of the complete crane. “With my industrial partner, we have already built a model of one of their existing cranes and demonstrated that it predicts the behavior of the real crane accurately. Now we have begun to use the model in our design work by looking at the likely impact of substitutions or design changes to individual components.”

The ability to model such changes before building the system is obviously extremely useful for the Aker Solutions designers, but the next stage of the project has the potential to fundamentally change their roles. “Ultimately, we want to use our models for design automation,” explains Bak. “In this approach we feed the system with the performance requirements of the finished product and with a library of options for hydraulic and mechanical components, then allow it to search for the optimum solution.”

Optimizing across hundreds of components and thousands of parameters would be time-consuming, difficult and unfeasibly dull for human designers, but a simulated model created using MapleSim can complete such a task rapidly and tirelessly. Even so, a viable system requires an efficient search algorithm and Bak plans to use the Complex Method. “In the algorithm, we populate the simulation with a number of randomly generated designs and it evaluates the performance of each,” he explains. “It then picks the poorest performing design and ‘mirrors’ it across the centroid of the remaining designs to produce a solution that should work more effectively.” This process is then repeated, with the worst performing design substituted each time, until the solutions converge on the optimum result.

Initially, Bak is using stability and accuracy as performance criteria, and, consequently, the optimum solution is the design yielding the lowest level of oscillations in the hydraulic system and with the best ability to follow the position reference fed to the control system. Later Bak plans to add other criteria such as price, robustness and long term reliability.

As the University of Agder project puts its models to ever more demanding uses, other aspects of MapleSim are becoming more important. “I am using MATLAB® and Simulink® to run the design optimization algorithm,” notes Bak. “Since MapleSim offers a direct link to that package, it is easy to integrate the two parts of the work.” Design optimization also makes considerable demands on the efficiency of computing packages, since a single optimization may require hundreds or thousands of separate simulations. “MapleSim runs fast and is computationally efficient and that is essential to keep run times down to a manageable level as we conduct larger and more sophisticated analyses,” he concludes.
Millions of shipping containers pass through sea ports each year, carrying anything from machinery and auto parts to shoes, toys, and frozen food. At modern ports, containers are unloaded onto docks, and then moved to stacking yards where Automatic Stacking Cranes and Ship to Shore Cranes stack them until they are ready to be loaded onto trucks or train cars. Containers must be moved quickly and accurately without interference from other containers, cranes, or vehicles. Any delays reduce profitability for the port, especially at large ports that move thousands of containers each day.

ABB Crane Systems is the world’s leading supplier of automation and electrical systems for container handling and bulk handling cranes, including automatic stacking cranes and ship to shore cranes. They are notoriously difficult to control because they use long ropes, and small disturbances can cause the containers to swing. Even without any external disturbances, the motion of the container itself can produce oscillations. Today, these cranes are required to lift heavier loads at higher speeds and to greater heights than ever before; however, this size increase is making the oscillation problem even worse. These oscillations and their suppression have been widely recognized as a major efficiency bottleneck by the shipping industry. ABB Crane Systems wanted to develop improved automatic crane controllers capable of suppressing the swinging motion, and hence improve their customers’ operational safety and profitability.

ABB Crane Systems asked Maplesoft Engineering Solutions experts to develop a new high-fidelity model of the container and ropes of large automatic cranes. Once developed in MapleSim, the system-level physical modeling tool from Maplesoft, the model was then exported as a Simulink® S-function to be used in testing. With the dynamic behavior of the ropes and container captured in the model, engineers at ABB Cranes were able to test their control strategies under a variety of scenarios and duty cycles. Since MapleSim allowed for the model structure to be quickly changed and the S-function regenerated, changes could easily be made in response to feedback from the operators.

The team at ABB Cranes uses MapleSim models for mechanical analysis, control algorithm development and to optimize operations. As a result, the engineers at ABB Crane Systems are able to improve the performance of their crane control systems, increasing container throughput for their clients.

"By using Maplesoft Engineering Solutions, we’ve saved our clients a lot of money while reducing our own development time from months to days," said Dr. Jonas Ohr, Tech Manager, Motion Control and Automation at ABB Crane Systems. "Using MapleSim to develop the initial plant model was significantly faster than trying to develop it in Simulink® alone, and the results were easily integrated into our toolchain. The Maplesoft Engineering Solutions team provided the expertise we needed to meet our project goals quickly and effectively."

These results increased profitability for ABB Cranes’ clients, particularly at very large ports moving thousands of containers each day.
Learn More!
These are just a few examples of how Maplesoft Engineering Solutions are being used in the design of complex machines in the manufacturing and industrial automation industries.
To learn more, visit: www.maplesoft.com/MachineDesign