Optimising Pre-Packaging Cycle-Times of LEGO Elements

C. J. Hellerup, S. S. Kristensen, T. H. Knudsen & V. J. Qvist

Department of Materials and Production, Aalborg University
Fibigerstraede 16, DK-9220 Aalborg East, Denmark
Email: chelle19@student.aau.dk, skri17@student.aau.dk, thkn17@student.aau.dk, vqvist17@student.aau.dk
Web page: http://www.mechman.mp.aau.dk/

Abstract
This paper aims to determine and reduce the settling time of various LEGO elements, when falling into a compartment of the wing unit. This is achieved through simulations in LS-Dyna, where a digital twin of the original design is made. The settling times of multiple bricks are then determined, by analysing their time-displacement curves. The results of the simulation model are then validated through practical experiments on the physical setup. Through a concept development phase, a new concept is proposed. This includes combining the technology of a stepper motor and a pressure sensor system to track the LEGO elements and open the gates, and by optimising the dimensions of the current design. The optimised design is modelled in LS-Dyna and the results are compared to the original design, to determine the overall reduction in settling time.

Keywords: LEGO, Pre-packaging, LS-Dyna, Finite elements, Settling time

1. Introduction

LEGO uses wing unit machines to make sure the correct amount of LEGO elements is packaged into each, bag by counting the amount of elements that fall through it. The LEGO elements need to settle on gates inside the wing unit, before they can drop to the next compartment, but LEGO does not know how long different elements take, before they settle. Currently, the cycle-time is determined by eyesight which is not precise and inefficient.

Therefore, this paper will focus on reducing the cycle-time by using LS-Dyna and practical experiments to calculate the optimal cycle-time for different elements, and by exploring different ways in which the wing unit can be modified to increase efficiency.

1.1 Wing Unit

The wing unit consists of two different compartment channels, each with two gates that can open and close, and a third gate that can direct the LEGO element two different directions, as seen in figure 1. The gates are assumed to be made of fibreglass reinforced epoxy, and the compartment is made from aluminium with the front side made of plexiglass.

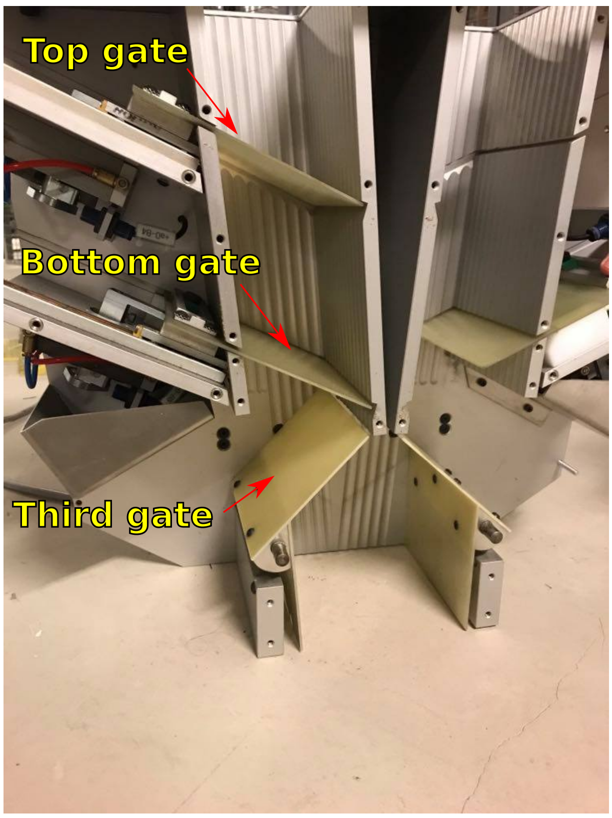

Fig. 1 Illustration of the wing unit's gates and the two compartments.

Currently, the gates are operated by pneumatic cylinders for closing and opening, but LEGO are in the process of changing this to stepper motors, to increase efficiency, as the gates will not have to open fully. The third gate is used to discard faulty elements or if too many have fallen into the wing unit.

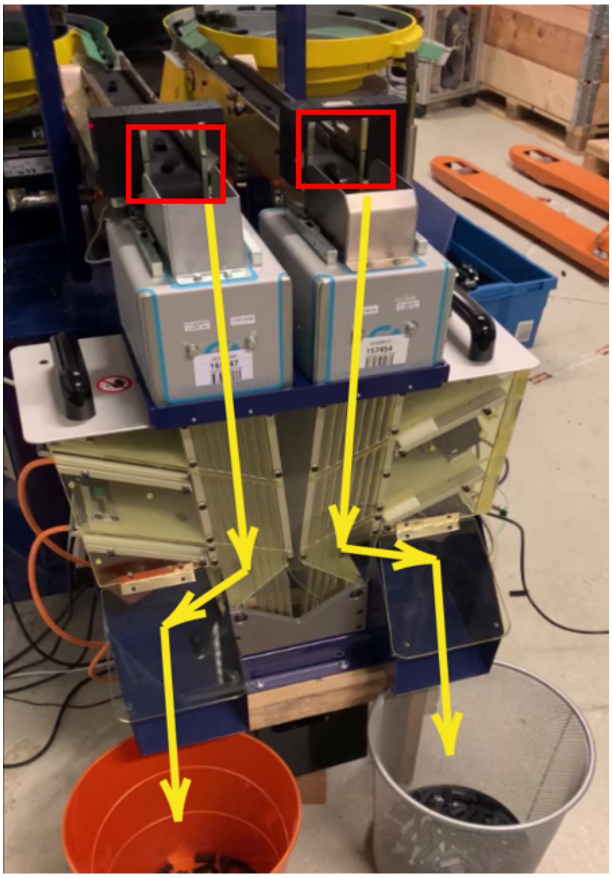

Fig. 2 The path the LEGO elements take when getting discarded (marked with arrows) and where they are weighed (marked with boxes).

In figure 2, the elements are weighed at the top marked with a box and the discarding process of the LEGO elements will follow the arrows if they are not within the weight tolerance. The correct elements will fall in a straight path (following the first arrow) down the compartments.
Currently, each gate can be adjusted to open and close at a specific time, depending on the type of element being packaged. The cycling-time ranges from 42 portions to 22 portions of elements per minute, where a portion ranges from 1-4 elements. The portion of elements per minute, depends on the LEGO element going through the wing unit, as some have a higher settling time than others.

2. Simulation Modelling

The fall of the LEGO elements are simulated, to understand the behaviour during the opening/closing processes of the gates. The simulation setup is illustrated in figure 3.

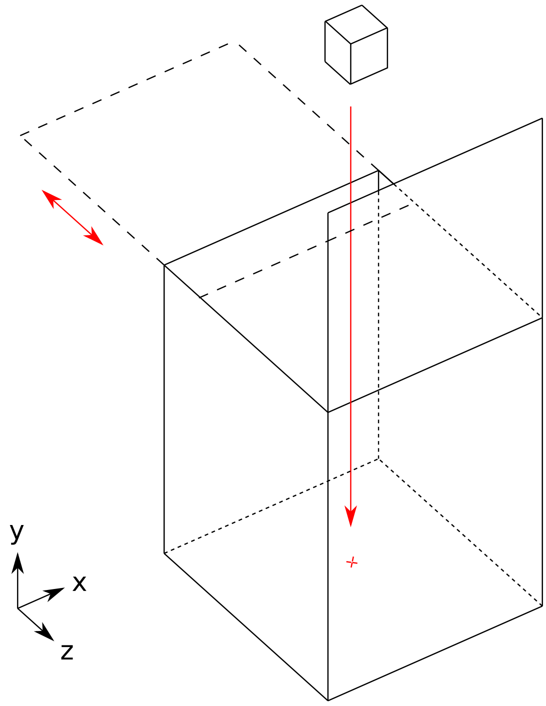

Fig. 3 Illustration of the simulation setup.

The setup in figure 3 is modelled in LS-Dyna, where the design of the compartment and the LEGO elements are modelled in CAD programs.

2.1 Modelling the LEGO Elements

From meetings with LEGO, the fast elements and slow elements are determined. Initially the slow elements are modelled and are illustrated in figure 4.

Fig. 4 The slow elements from LEGO.

One of the challenges faced, when modelling the LEGO elements, is the degree of detail. Higher degree of detail requires a finer mesh, which increases the computational time. Therefore, an analysis is conducted, where the degree of detail is gradually increased, to determine the appropriate degree of detail. For the analysis, the 2x1 brick fast LEGO element is used, where the order is: no detail, low detail, medium detail and high detail. The models are illustrated in [1]. The degree of detail is analysed, by examining the settling time and the computational time. The settling time is determined as the slowest settlement in the x-, y- and z-direction and are listed in table I. How the settling times are determined are explained in [1].

	Avg. settle time	**Avg. comp. time**
No detail	1330ms	11h and 18min
Low detail	1230ms	15h
Medium detail	1270ms	25h and 5min
High detail	1100ms	27h and 2min

Tab. I Settling points for the detail models.

From table I it can be seen that the settling time decreases, with increasing detail, but the computational time also increases. From the analysis, it is concluded that a high degree of detail is needed. This is chosen as a compromise between computational time and precision, where precision is valued highest.

2.2 Description of Simulation Model

The process of setting up the simulation model is described in [1]. The gate opens fully in 220 ms and closes with the same speed. The gate is set to open after 500ms, as the LEGO element needs to settle on the top gate before the gate opens.

To make the fall of the LEGO element realistic, a MATLAB script is created to rotate the LEGO element randomly and furthermore translate the brick randomly across the xz-plane, however, it will stay within the boundaries of the compartment, see figure 3. This way random falls can be simulated, whereby the average settling time for each element can be determined.

The falls are analysed through a MATLAB script. The time-displacement data from the centre node of the simulated LEGO element is obtained from LS-Dyna. The data is then loaded into the MATLAB script, from which the minimum and maximum peaks points are determined. From the peak points, the settle time is set to be when the distance between the peak points is below a given value. This can be adjusted for the time-displacement curve in each of the three directions.

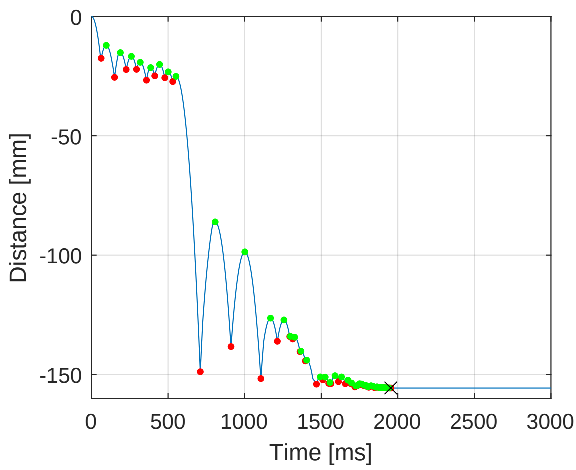

Fig. 5 The y-displacement of the centre node in the round plate LEGO element. Minimum points are marked with red and the maximum points are marked with green.

The overall settling time is then determined from the maximum of the settling times in each of the three directions. The given value between the peak points, as mentioned earlier, can be adjusted to fit when the LEGO element is assumed to be settled.

The precision of the results depend on the amount of finite elements used in the simulation. Therefore, an analysis is conducted, to determine how many finite elements are needed to discretize the LEGO elements. The amount of finite elements for the compartment is kept constant and the element size is gradually increased from 0.5 - 5.0. The result is illustrated for the round brick with open stud element in figure 6.

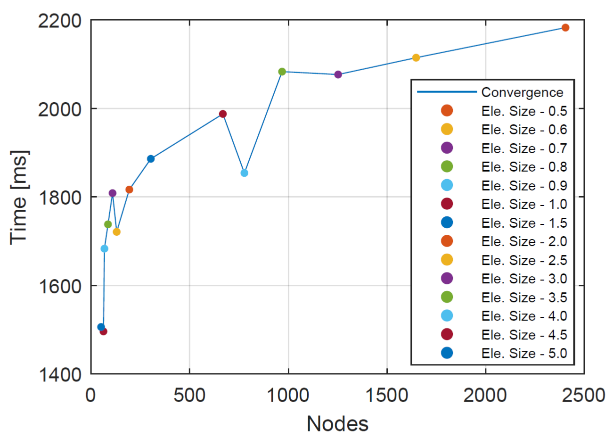

Fig. 6 The convergence plot for the round brick with open stud element.

From figure 6, the settling time never converges. Therefore, to maintain the precision of the results, the smallest element size tested, which is 0.5, is used.

2.3 Validation of the Simulation Model

To validate the simulation model, experimental procedures have been performed on the supplied wing unit from LEGO. A LEGO element is placed on the top gate (see figure 1), which is then manually opened. The procedure is filmed with a frame rate of 240fps, and a video tracking analysis is then performed in the software Tracker. The experimental setup can be seen in figure 7.

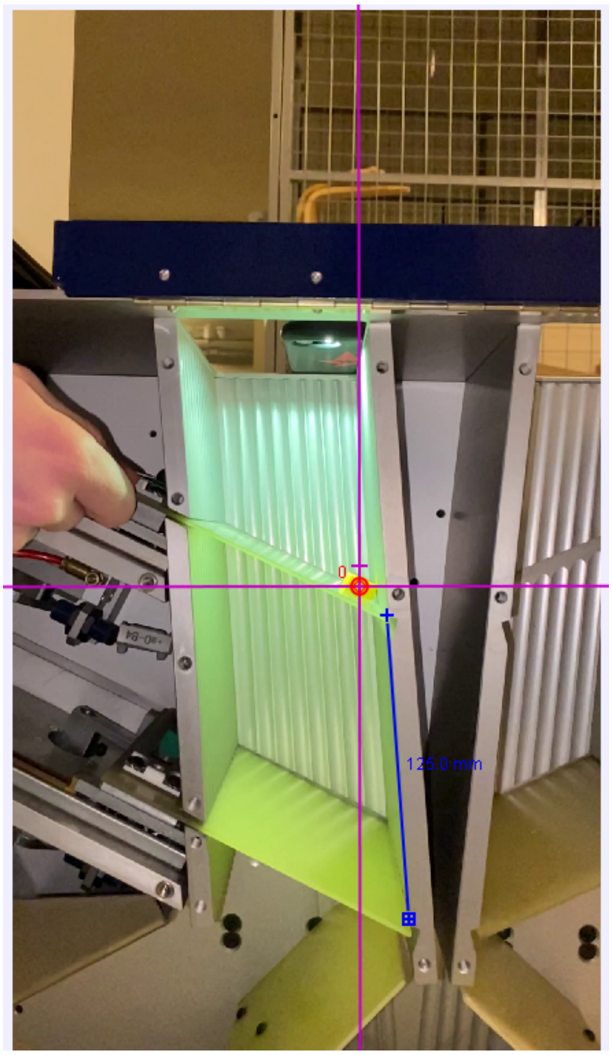

Fig. 7 The experimental setup and the video tracking analysis.

The fall of each LEGO element is traced and the displacement in the x- and y-direction is obtained and compared to the time displacements from the simulations. The z-displacement cannot be traced, and is therefore not compared to the simulations. The round plate element validation is demonstrated in figure 8.

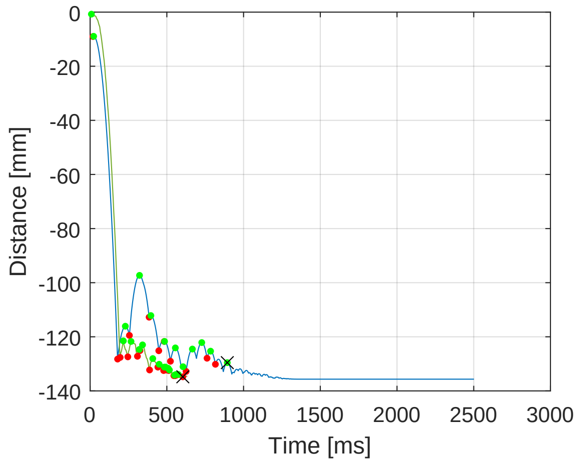

Fig. 8 The validation plot for the round plate element. The green plot is the experimental data and the blue plot is the simulation data.

To reach the same settling time for the simulation, a grey box model is used. Different parameters such as the static friction coefficient, the shell thickness and the material models influence the settling time. These are analysed respectively. From the friction analysis, a relation between the static friction coefficient and the settling time was found, as shown on figure 9.

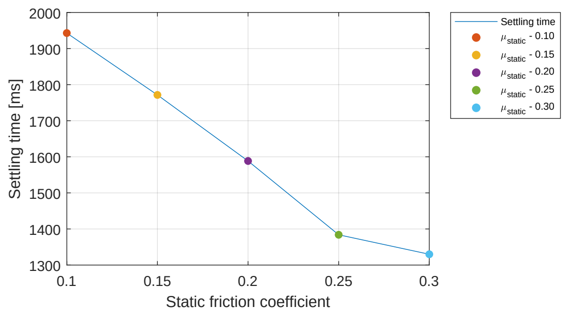

Fig. 9 The influence of the static friction coefficient on the settling time, with a initial rotation of 1 $\frac{m}{s}$.

A validated model could not be achieved that had the same settling time as the practical experiments, 911 ms to 573 ms. However, an elastic and viscoelastic material model was added to the simulation to better represent the physical model. Furthermore a margin of error was introduced, where the average deviation between the simulation and the real world model was found. This deviation was found to be 37.14% and will be used to compare the simulation to the real world model. The results for the validated model can be seen in table II and on figure 10.

	Settling time [ms]
x-disp.	573
y-disp.	493
z-disp.	**607**

Tab. II The settling times for the final validated model.

The settling time has the highest value in the z-direction, of 607ms.

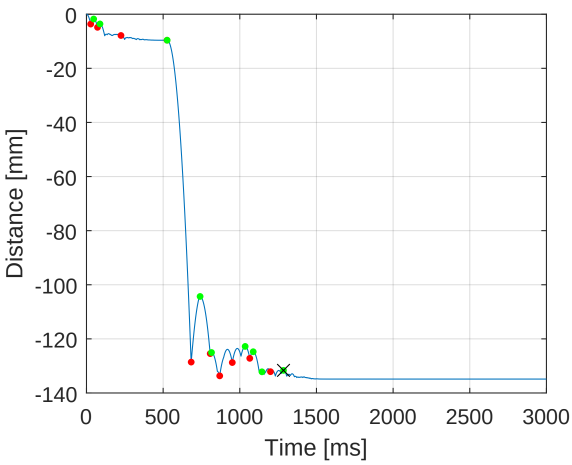

Fig. 10 The y displacement on the final validated model.

3. Concept Development

Through the concept development phase a morphological analysis is used to find a concept which will reduce the cycle-time, where Pugh's concept choice is used to narrow down the concepts from the brainstorm. First, the partial functions that will have an effect on the cycle-time is found and listed below:

- Open/close - How does the gate open and close?
- Fall time - How is the fall time reduced?
- Settling - How does it reduce the settling time once it hits the bottom gate?
- Tracking - How does it know when to open the gate?

From the partial functions, a brainstorm session is carried out, to find different ideas for each function, thereby creating different partial solutions. From these partial solutions the final concept was found to be;

- Stepper motor
- Dimensions
- Gate angle
- Pressure sensor

3.1 Description of Concept Choice

The partial functions in the final concept is described below.

3.1.1 Stepper Motor

LEGO are already in the process of adapting stepper motors to their current wing units, so it becomes an easy adaptation process, as most of the work has already been done. The advantage of a stepper motor is the more accurate control compared to other electric motors.

3.1.2 Dimensions and Gate Angle

Currently the dimensions and gate angle are potentially sub-optimal. To optimise this, an optimisation problem can be set up to find the different factors. These factors consists of height, width and depth, where the last factor to consider is the gate angle. The advantage of optimising the model is to get the optimal conditions for the compartments resulting in a desirable settling time.

3.1.3 Pressure Sensor

Currently, the gates are opened by a pre-defined time interval, which is set by the machine operator. By implementing a pressure sensor the gate would open at different times for each individual LEGO element, by determining whether there is a load applied to the sensor. This will reduce the cycling-time of the wing unit.

4. System Design

The optimisation of the dimensions and the development of the pressure sensor system will be undergone in this section.

4.1 Optimisation of Dimensions and Gate Angle

The concept strives to optimise the dimensions of the compartment and the angle of the gate. This is achieved through an optimisation scheme, where an iterative approach is taken. Initially, an objective function is established. The objective function is defined according to the variables illustrated in figure 11.

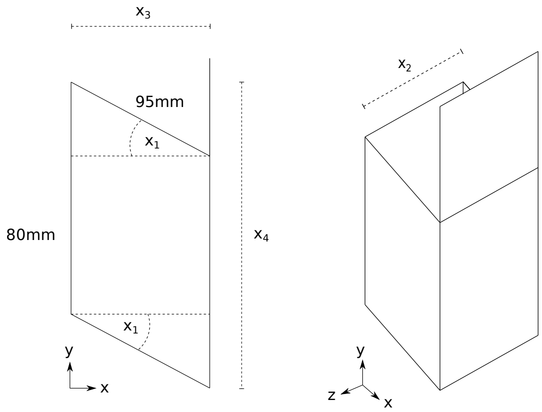

Fig. 11 Sketch of the variables included in the objective function.

In total, four variables need to be optimised. The width and height are dependent of the gate angle and can be expressed by equation 1.

$$x_3 = cos(x_1) \cdot d_2 \tag{1a}$$
$$x_4 = d_1 + 2 \cdot (sin(x_1) \cdot d_2) \tag{1b}$$

where

x_1 = The gate angle
x_2 = The depth of the compartment
x_3 = The width of the compartment
x_4 = The height of the compartment
d_1 = Predefined distance between the tip points of the gates, set to 80mm
d_2 = The length of the gate, set to 95mm

The objective function is used to describe the settling time according to the defined variables. To study the influence of the variables, 10 simulations are performed for each variable, where the size is reduced in intervals. From these simulations, regression analyses are performed, where second order polynomials are established, written in the form of equation 2. These describe the influence of the variables respectively on the settling time. The constants for the polynomials are listed in table III.

$$f(x_i) = a \cdot x_i^2 + b \cdot x_i + c \tag{2}$$

	a	b	c
$\mathbf{f(x_1)}$	0.0884	-30.7	2317
$\mathbf{f(x_2)}$	0.0500	-8.81	1901
$\mathbf{f(x_3)}$	-0.250	44.3	-308
$\mathbf{f(x_4)}$	0.0721	-10.9	1499

Tab. III Coefficients for the different regressions.

The expressions are combined, to form the settling time function (ST), defined in equation 3

$$ST(x_1, x_2) = \frac{1}{4} \cdot \sum_{i=1}^{4} f(x_i) \tag{3}$$

The ST-function is subject to two inequality constraints, defined in equation 4, which constrains the depth, width and height to being larger than 40 mm each. Since the width and height are expressed by the angle, the constraint is defined by the angle.

$$0 \leq x_1 \leq 65 \tag{4a}$$
$$40 \leq x_2 \leq 140 \tag{4b}$$

The ST-function is plotted in figure 12, where the red square indicates the boundaries, defined by the constraints.

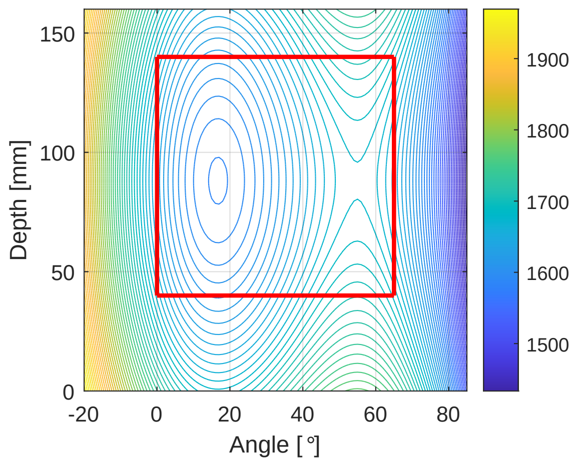

Fig. 12 Contour plot of the objective function. The red square indicates the inequality constraints which are applied.

From figure 12, a minimum can be observed. To determine the location of the minimum, sequential quadratic programming (SQP) is applied. Through SQP the ST-function is minimised iteratively, until convergence is reached. The result is plotted in figure 13.

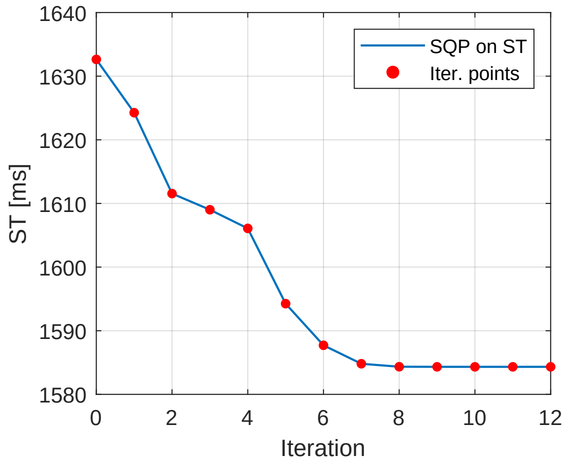

Fig. 13 Plot of SQP applied for minimisation of the ST-function.

The plot converges at 1584 ms, with the variables defined in table IV. The table shows a decrease in size for the angle, depth and height and an increase in width. This corresponds well to the regressions seen in [1].

	Var.	**Initial**	**Optimised**
Angle	x_1	26.5°	16.7°
Depth	x_2	140mm	88mm
Width	x_3	84mm	91mm
Height	x_4	170mm	135mm

Tab. IV The initial and optimised variables.

The dimensions of the compartment and the angle of the gate is adjusted, and the model is simulated. From the simulations, a settling time of 1571 ms is reached, which is 160 ms less than the initial model.

4.2 Pressure sensor test

To determine if a pressure sensor would reduce the cycle-time of the wing unit, a code was written, and visualised as a pseudo-code in figure 14.

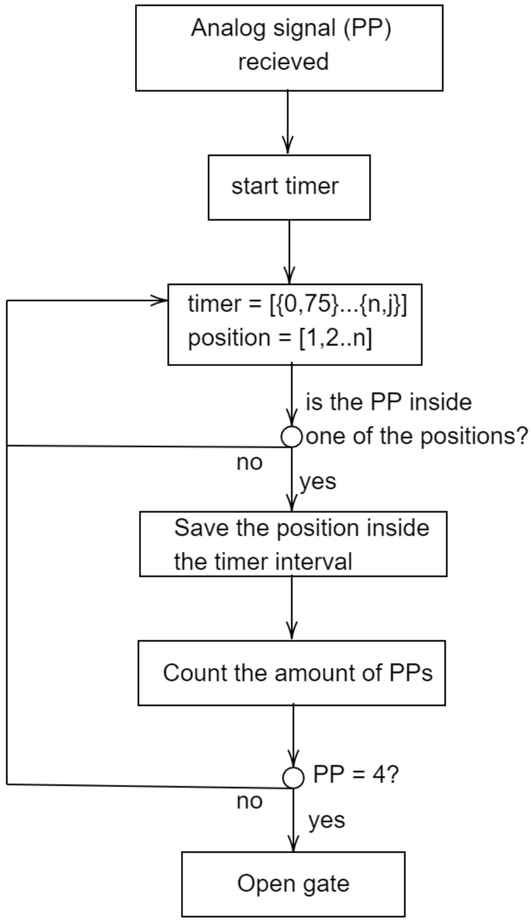

Fig. 14 Pseudo-code for the pressure sensor system.

As described in figure 14, the timer continuously checks the time intervals from [0:75,..,N:J], making it possible to set an upper and lower bound for the problem. Hereafter the position, from [1,..,N], determine what time-interval the analogue signal, described as pressure points (PPs), is received in. The PPs are then saved and counted, such that one can determine the number of PPs that is received in one of the positions. Lastly, if the number of PPs is equal to four then the gate will open.

Several tests for this particular system was undergone, see [1] for the procedure of the tests. The tests concluded that the pressure plate system could be used to open the gate when the LEGO element settled and occasionally one position before. However, for the fast LEGO elements, a predefined opening time for the gate would have to be used, since they did not exert enough PPs for the pressure plate to open.

5. The Final Model

From the results found in previous sections, a final model is developed and has been simulated. The dimensions have been fitted to the dimensions found in subsection 4.1, and the pressure plate system has been applied. Furthermore, the validation keywords in LS-Dyna have been used, to set up the simulation model. The time-displacement curves in each direction can be seen in [1]. The settling time in each direction is listed in table V

	Settling time [ms]
x-disp.	**524**
y-disp.	425
z-disp.	504

Tab. V The settling times for the final model.

The settling time of the round plate LEGO element is 524 ms which is a reduction of 83 ms (14% reduction), from the settling time of 607 ms in the validated model, described in subsection 2.3.

An error is spotted in the simulation, that can be read in [1].

5.1 Pressure plate system

The pressure plate system implemented in the final model determined an opening time of 524 ms, which is exactly where the settling of the round plate would occur. Hereby, this system could be used to automatically open the gate for this particular LEGO element.

5.2 Comparing the Validated Model and the Optimised Model

To determine if the optimised model improves the problem stated by LEGO, a comparison between the validated model and the optimised model is performed. From subsection 2.3 the settling time from the validated model was found to be 607 ms. Whereas the optimised model's settling time was found to be 524 ms in the previous section. This means, that the optimised model has reduced the settling time by 83 ms.

6. Conclusion

A model based on the obtained information was developed in LS-Dyna, from which it was possible to simulate the fall of a LEGO element in the original wing unit compartment. This model was compared to practical experiments and thereby validated. The validation was done by introducing a margin of error, which would be used on the obtained results, throughout the report.

The validated model was used as an offset, for testing concepts which would reduce the settling time of the round plate LEGO element. The final model, consisted of combining a stepper motor with a pressure sensor system and dimension changes of the original compartment. The pressure sensor system was developed based on practical experiments and simulations. The dimensions of the compartment were optimised, by applying sequential quadratic programming. From optimisations made on the original design, the LEGO element now settles at 524 ms and the gate opens at the same time, by using the pressure sensor system. This is a reduction of 83 ms from the validated model of the original design.

Acknowledgement

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References

[1] C. J. Hellerup, S. S. Kristensen, T. H. Knudsen, and V. J. Qvist, Optimising Pre-Packaging Cycle-Times of LEGO Elements. Aalborg University, 1st ed., 2021.