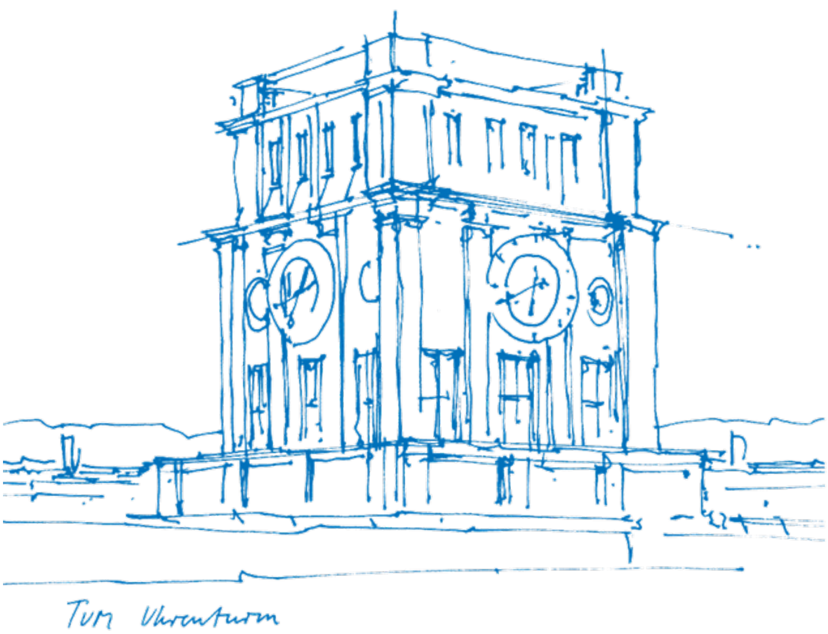
Chair of Information Systems and Business Process Management (i17)
Department of Computer Science
TUM School of Computation, Information and Technology
Technical University of Munich

Master's Thesis in Informatics

Nicolás Mario Arteaga García

Cotton Candy Digital Twin: Prescriptive Creation of Digital Twins



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Titel der Abschlussarbeit

Thesis for the Attainment of the Degree
Master of Science

at the TUM School of Computation, Information and Technology,
Department of Computer Science,
Chair of Information Systems and Business Process Management (i17)

Examiner
Prof. Dr. Stefanie Rinderle-Ma

Supervised by
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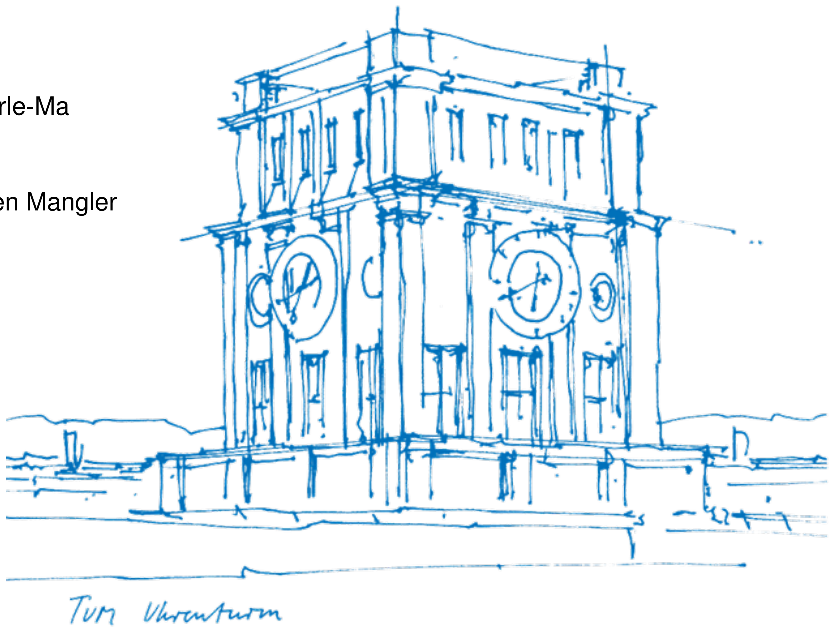
Submitted on
31.07.2025



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This thesis was not previously presented to another examination board and has not been published.

Garching, 31.07.2025 Nicolás Mario Arteaga García

Abstract

150 - 180 words

Keywords: Digital Twin, Cotton Candy, BPTM

Include three to five words, phrases, or acronyms as keywords.

Contents

List of Tables

List of Figures

Introduction

For exposes, create this chapter, plus start with chapter 2 (Related Work).

Motivation

Why are we doing it? About 1 page.

As industries evolve, the ability to optimize processes while minimizing waste has become increasingly important. Digital twins (virtual models of physical systems) are transforming how we monitor, analyze, and improve these processes. While reactive digital twins respond to events as they occur, providing immediate but limited feedback, predictive digital twins forecast potential outcomes based on historical and real-time data, allowing proactive adjustments. However, the growing focus on prescriptive digital twins introduces a new frontier: systems that not only predict outcomes but also recommend specific actions to achieve goals such as improving efficiency, reducing energy consumption, or enhancing product quality.

This thesis explores the development of prescriptive digital twins using the Cotton Candy Automata, a robotic system developed in the chair to automate cotton candy production, as a practical and measurable test case. This scenario provides an ideal environment for evaluating two distinct approaches to digital twin design—bottom-up and top-down—by analyzing key variables such as heating time, spinning duration, sugar amount, and energy usage. Each approach takes a unique perspective:

Bottom-Up Approach: Focuses on physical measurements and process models, leveraging real-time sensor data to guide system optimization.

Top-Down Approach: Relies on historical data and advanced computational methods, including interpolation, selection of closest historical values, and machine learning models like Recurrent Neural Networks (RNNs), to model and optimize the system.

The goal of this thesis is to provide a comprehensive evaluation of these two approaches, comparing their strengths, limitations, and suitability for different scenarios. By analyzing metrics such as energy savings, time efficiency, and production quality, the research aims to determine which method offers the greatest value (for this process/for specific process types?). Applying both methodologies to the same scenario enables a deeper understanding of their trade-offs and practical implications, offering insights that can guide future efforts in digital twin development.

Ultimately, this work contributes to the broader understanding of how to design and implement prescriptive digital twins, providing actionable recommendations for selecting the best approach based on system goals, constraints, and operational contexts.

Research Questions

At least 3 questions. They should not be answerable yes/no. Questions should be questions (1 sentence). But you are allowed to explain them in more detail. In the explanation also tell how you plan to prove that your potential future solution is good.

About 1 page.

Fexamples: (1) How can we design and implement prescriptive digital twins for the Cotton Candy Automata? (2) MMM What are the strengths and limitations of each approach, and how do they impact key metrics such as energy savings, time efficiency, and production quality?

Contribution

What will/have I do/done that nobody else has done before. About 1/2 page.

Methodology

Design Science in Information System (Hevner). How are we doing research?

(1) Summary what design science is (it uses stakeholders, artefacts, steps, ...).

(2) What are the stakeholders, artefacts, steps for MY case. What does it mean for my thesis?

About 1.5 pages.

This work follows the Design Science Research (DSR) paradigm as defined by Hevner et al. [1]. The DSR approach provides a structured framework for the development and evaluation of innovative artefacts that solve real-world problems in a rigorous and methodologically grounded manner.

In the context of this thesis, the central artefact is a digital twin system for a cotton candy production robot. This artefact comprises both the virtual representation of the physical process and the accompanying infrastructure for capturing environmental and process-related parameters (e.g., humidity, input sugar, and runtime), as well as metrics of product quality (e.g., volume, weight, and fluffiness).

The digital twin is iteratively refined through cycles of design and evaluation, in accordance with the DSR methodology. The system is deployed in a real-world production context and evaluated based on its ability to improve product quality and production efficiency under varying conditions. This dual focus on practical applicability and measurable improvement ensures that the artefact addresses both relevance and rigour — the core criteria of Hevner's framework.

Evaluation

How will I evaluate that my proposal is good. This ties into the research questions.

About 1 page.

Structure

Which chapters will my thesis have, and what are they all about. About 1/4 page.

Related Work

Related Work - There is a girl with long dark hair doing a thesis on digital twin as a research analysis. ask her per discord

google scholar in-title digital twin / business processes, search queries that give you less than 20 papers and decide 1 or 2 papers in the end. How many papers did we eliminate? why? bc too

backgorund 1-2 sentences -> Why am I doing something different to this related work

Final max 4-5 papers that really relate to what Im doing

THis one doesnt work bc, its for bridges and civil engineering https://www.sciencedirect.com/science/article/pii/S01410296230

this one looks good : https://www.sciencedirect.com/science/article/pii/S0360835224003620

Thermal Study on Cotton Candy

Cotton candy consists of spun sucrose that cools rapidly, forming a mostly amorphous structure — but: • Over time, this amorphous state can convert into crystalline form. • The ratio between crystalline and amorphous sucrose affects: • Texture • Stability • Taste • Shelf-life

This paper provides very solid experimental data on how production parameters influence the physical structure (crystalline vs amorphous) of cotton candy.

Crystalline is . . . Amorphous is . . .

Knowing how production parameters (like gas environment) affect structure can inform optimal production recipes. We are not gonna compare CCA vs CCN, since we are always using Normal Air but We learn about the importance of humidity, and want to use it for our Data Recollection since this is important For the Prescriptive twin design.

This helps with us taking the decision how to measure the quality of CC when doing data recollection and giving a note to the process.

What makes it difficult is that the changes are fine and little, and we dont really know if we are gonna be able to distinguish them, but we did research and will introducte this in the Solution Design.

Solution Design

• What is the physical structure of cotton candy? What aspects define "quality" of cotton candy? • What are the key factors that affect quality? • How does it change with production parameters? What we already learned doing cc is -> The notes from the notion

• What is the physical structure of cotton candy?

Cotton candy is primarily composed of spun sucrose, which can exist in two main forms:WHat we saw in the paper. . .

What aspects?

YES: Volume density -> How much sugar is in a given volume -> Weighing sample and measuring volume (water displacement) => Doing this wiht a trichter that has the exact volume written. How does it change wiht more or less humidity?

NO: Visual appearance -> Fiber structure, color, consistency -> Visual inspection, photography + image analysis (even with your phone and Python/OpenCV) => we are not gonna do this because we learned that it is not really possible to distinguish the fibers with the naked eye. Its a full master thesis on its own

NO: Texture & mouthfeel -> Stickiness, softness, “melt-in-mouth” -> Manual touch test, break force => Stickiness is interesting to measure but probably difficult more on it later NO: Hygroscopic behavior -> Stickiness as it absorbs moisture -> Weighing sample over time at room humidity => This is very interesting, takes time to measure but hey -> NO BC WE WILL CREATE THEM IN DIFF ENVIRONMENTS AND CANNOT CREATE A CONTROL CAPSULE

YES: Crispness vs softness -> Related to crystallinity -> Compression test (kitchen scale or small force sensor) => It would mean measureing how much compression force is needed to break the fibers, very difficult, we build a model that we could test between CC and after measuring volume we weighted it, we tested this and that and concluded. . .

B. Compression Test • Use a small kitchen scale or force sensor. • Press gently until collapse starts. • Record maximum weight/force applied. • Amorphous cotton candy tends to be softer; more crystalline samples resist compression.

NO: Structural stability -> How long it holds shape over time -> Timed visual check at room conditions => Takes long to test,

NO: Taste (subjective) -> Flavor preception is too subjective so we will not do this, but it is important to note that it is a factor in quality perception.

• How does it change with production parameters?

How can we change the environment and control so that production parameters are changed • Humidity: Higher humidity leads to more stickiness and faster recrystallization. -> How to simulate Humidity? The gas environment during spinning directly changes how much of the sucrose becomes crystalline vs amorphous. • More oxygen & moisture → more crystallization. • Less oxygen & low moisture (like nitrogen or dry air) → more amorphous content. -> We cannot change the environment, but we can change the humidity of the process with: - Airflow / fans -> Stronger air movement near spinner -> Helps dry fibers during flight/creation, reduces moisture pickup. -> YESSSS LETS DO THIS

Affect on more humidity durign spinning -> Fibers may break sooner, become shorter, thicker. fibers stick together more. and after spinning -> Fibers collapse and shrink, Loss of volume (shrinkage), stickiness increases. what about compression? Immediately after spinning (fresh) - Fibers in humid air are thicker, stickier → denser structure → higher compression resistance initially (less fluffy, more "compact"). - Less air trapped between fibers → more force needed to compress. Shortly after spinning (as moisture is absorbed) - As fibers absorb moisture, they soften → compression force quickly drops. - Structure collapses under small loads.

Compression is kind of complicated to test since: Actually, at high humidity: • At first → more compact = higher compression resistance. • But as time passes → absorbs moisture → weaker structure = lower compression resistance.

In contrast, at low humidity: • The fibers stay dry, fluffy, and light. • Lower compression resistance but much better structural stability over time.

Humidity Level Result that we think we could achieve: Low RH < 30% Light, fluffy, large volume, fine fibers. High RH > 60% Denser, smaller volume, coarser fibers, faster shrinkage.

• Temperature: Higher temperatures can lead to more amorphous structure, but too high can cause burning. We have no control over this, as we are gonna see in the Solution Design, we are using a machine that always stays at the same ratio of temperature when at work. -> What we can control and change is the Cooking time, so the temperature that the head had when inserting the suagr and the time that we let the cotton candy get created, and let the arm roll. -> What this hopefully gives us is the change in structure that we can test with the compression test and a bigger volume.

• Spinning speed: Faster spinning may lead to finer fibers, affecting texture. Spinning speed (Higher RPM) Creates finer fibers, helps counteract thickening effect of humidity. -> We cannot control this. The given machine always spins in the same speed.

- One big variable that I had at the start was the Sugar amount. Thinking naively, I thought that more sugar would lead to more volume, but this is not the case. The amount of sugar in the process is always the same, and we are not changing it. We are always using the same amount of sugar for each production, which is 10 grams. -> Adding more won't help volume, might increase stickiness. And we are not measuring this change in stickiness as we saw before.

- Sugar formulation -> Use anti-hygroscopic additives (e.g., small % of maltodextrin or stabilizers) -> Slows moisture absorption. Often used in industrial production. We are not chanign the sugar formulation. We are always using the same sugar from the supermarket for making it easier to reproduce the results.

What we learned empirically doing CC

- write times, forms, radius why that radius etc etc etc

=> We can create a formula of how we think it behaves, that we can compare afterwards in the Data Recollection Evaluation.

Prescriptive Digital Twin Flow

- We have an Environment that we cannot control, but we can measure it. - We have a process that we can control, but what exactly? THe time of cook? (Yes) The amunt of sugar? (Yes, but doesnt impact), The heating up before spinning? (Yes, but only energy savings impact) The . . . - We have a product that we can measure and evaluate the quality, but how? (First measure the Volume and then the compression stress, etc)

With 200 points of this data we can create a Model that can forecast the quality mark of the product looking at the ENV and the Process Rules. With Desicion Trees since this and that. . .

With the Forecasting we can change the Process rules to imporve the quality of the product. How? With Decision Trees? Trasvering back? How should it be done? I dont know yet.

Figure 1
My Figure Caption

A note describing the figure

Implementation

Product Quality Measurement

During the data collection phase, a structured dataset was compiled by recording relevant product-related parameters during each cotton candy production run. These measurements include the input sugar weight, the final cotton candy weight, estimated volume based on geometry, and the derived Fluffiness Index. This enabled consistent tracking across experiments and formed the basis for downstream quality evaluation and performance comparisons for the Model.

Weight Measurement

The input mass of sugar for each production run was manually measured using a precision scale with a readability of 0.01 grams. To determine the output mass of the produced cotton candy, the final product (including the stick) was weighed immediately after production using the same scale. The net weight of the cotton candy was then computed by subtracting the known weight of the stick, which was measured prior to the experiment and kept constant across all runs.

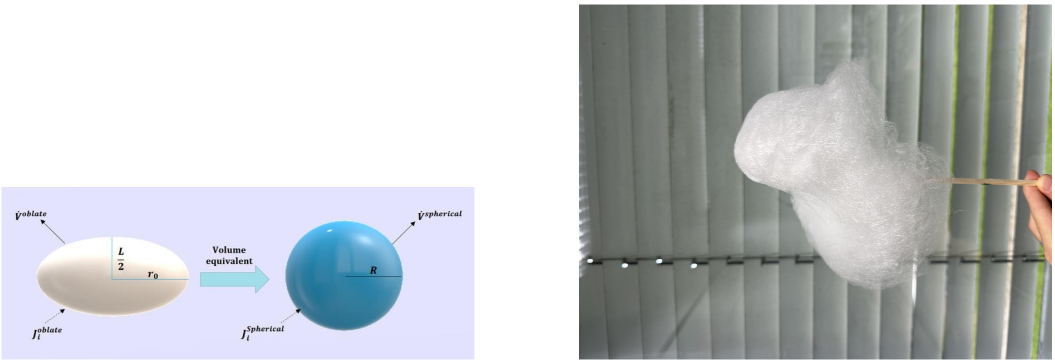
Accurate weight measurement was essential for evaluating the amount of produced cotton candy and for computing derived metrics such as the quality and Fluffiness Index. All weights were recorded in grams with a precision of two decimal places.

Volume Estimation

To approximate the spatial characteristics of the cotton candy output, the product was modeled as an oblate spheroid — a flattened ellipsoid shape that approximates the typical morphology observed during production.

Figure 2

Comparison between geometric approximation and real cotton candy morphology



(a) *Idealized oblate spheroid*

(b) *Actual cotton candy output*

Measurements of the maximum width and height were taken manually using a standard ruler immediately after each production run. Based on these dimensions, the volume V was estimated using the standard formula for an oblate spheroid:

$$V = \frac{4}{3}\pi a^2 c$$

where a is the equatorial radius (half of the width) and c is the polar radius (half of the height). Although this approach does not capture fine-grained structural variations, it offers a practical and repeatable method to compare volumetric differences across runs.

To further assess structural quality, a Fluffiness Index was derived as:

$$\text{Fluffiness Index} = \frac{V}{\text{Weight}}$$

This index serves as a proxy for the density of the cotton candy, with higher values indicating a lighter, airier structure. The same procedure and tools were applied consistently across all production runs to ensure internal comparability.

Limitations in Volume Measurement

The estimation of cotton candy volume relied on manual measurements of width and height, followed by geometric approximation. While this method provides a reasonable basis for comparative analysis, it is subject to several limitations: (a) the inherently irregular and fragile structure of cotton candy, (b) potential observer bias during manual measurement, and (c) the assumption of a regular geometric shape. As such, the absolute values of estimated volume should be interpreted with caution. However, because the same procedure was applied uniformly across all experimental runs, the relative differences and trends derived from this method remain valid for assessing the effects of the digital twin optimization.

Evaluation

Product Output Quality

Test for github of changing things here

The quality of the cotton candy produced in each run was assessed using the previously introduced weight and volume-based metrics. In particular, changes in product volume and the derived Fluffiness Index were analyzed across multiple runs to evaluate whether the digital twin contributed to a measurable improvement in output quality.

Discussion

Measurement Limitations

While the estimation of product volume provided useful insights into structural quality, it is subject to several limitations. The irregular shape and delicate structure of cotton candy introduce measurement uncertainty, especially when relying on manual tools such as a ruler. Furthermore, the assumption of an ideal oblate spheroid shape simplifies the actual morphology, which may vary significantly across runs.

Despite these limitations, the same procedure was applied consistently throughout the experiments, ensuring the validity of comparative trends. For future work, more precise volume estimation techniques such as 3D scanning or photogrammetric analysis could be explored to capture the complex geometry of the product more accurately.

Conclusion

Bibliography

[1] A. R. Hevner, S. T. March, J. Park, and S. Ram, "Design science in information systems research," *MIS Quarterly*, vol. 28, no. 1, pp. 75–105, 2004. DOI: 10.2307/25148625.

Appendix

Table 1
Your first table

Value 1	**Value 2**	**Value 3**
α	β	γ
1	1110.1	a
2	10.1	b
3	23.113231	c

A note describing the table.

Figure 3
My Figure Caption

A note describing the figure