

Modelling and Evaluation of Third Molar Protocols using UPPAAL

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The management of third molars involves a range of clinical challenges, particularly in deciding whether to extract asymptomatic third molars or to adopt a wait-and-see approach. This research used the UPPAAL verification toolbox to model and evaluate different third molar management protocols, focusing on optimizing clinical outcomes, healthcare costs, and patient well-being. Our formal modelling approach compares a preventive protocol (based on KIMO guidelines) versus a symptomatic protocol. Results demonstrated that the preventive protocol leads to a slightly higher average number of extractions per patient (3.95 vs. 3.88; a 1.8% increase), reflecting its proactive nature. However, it significantly reduces symptomatic extractions by 65% (from 3.02 to 1.07), indicating effective early intervention. The average incidence of complications per patient was marginally higher under the preventive protocol (1.64 vs. 1.63), but complication rates per extraction were comparable between the protocols. Notably, severe complications such as alveolitis trended lower under the preventive approach (33.9% vs. 44.4%). The preventive protocol also reduced average healthcare costs per patient by 24.6% (\$424.044 vs. \$562.748), primarily due to the additional extractions that occur in the same operation, and lower complication expenses due to extraction happening at a young age. This research supports the preventive protocol as the more effective strategy for third molar management, aligning with KIMO guidelines and emphasizing the importance of early intervention to optimize patient outcomes and reduce healthcare costs.

Additional Key Words and Phrases: Third molars, UPPAAL, Formal Methods, management protocols.

1 INTRODUCTION

Third molars, commonly known as wisdom teeth, are the last set of teeth to develop in humans, usually emerging between the age of 17 and 25. Due to evolutionary changes and variations in human jaw size and diet, there is often insufficient space in the mouth for the third molar to develop. As a result, third molars are prone to complications such as impaction, infection, and damage to adjacent teeth.

The management of third molars, particularly asymptomatic third molars, remains a subject of ongoing debate. Dental professionals often face the challenge of determining whether to recommend prophylactic removal or adopt a wait-and-see approach. The Kennisinstituut Mondzorg (KIMO) [2] supports the preventive removal of asymptomatic third molars, emphasizing the importance of preventing potential damage and complications. Preventive removal at a young age (between 16.5 and 18.5 years) is recommended because the roots of the third molar are not yet fully formed, minimizing the risk of damage to the inferior alveolar nerve (mandibular nerve).

However, this decision involves complex trade-offs. Preventive extraction may lead to unnecessary extractions, increased healthcare costs, and potential complications, while delayed treatment may result in more complex extractions with higher complication rates.

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This research develops a formal model of third molar management protocols using UPPAAL to evaluate the different strategies, considering patient characteristics, clinical outcomes, and healthcare costs.

Research question: *What is the most effective protocol for managing third molars, optimally balancing postoperative complications, patient well-being, and healthcare costs?*

With the following sub-questions:

- (1) What is the average extraction frequency per patient under each protocol?
- (2) What is the average incidence of complications (pain, infection, swelling, trismus, alveolitis, and paresthesia) per patient?
- (3) What are the average healthcare costs per patient?

For this research, UPPAAL [5] is used to model and analyze third molar management protocols. Developed collaboratively by Uppsala University and Aalborg University, UPPAAL is a formal verification tool designed for real-time systems based on timed automata. These automata extend finite-state machines with real-valued clocks, enabling the modeling of systems that evolve in continuous time. In UPPAAL, systems are represented as networks of timed automata operating in parallel. Each automaton can read, write, and update variables, which is similar to constructs in programming languages, which together with clock constraints define the system state. Transitions occur when edges are fired, either independently or through synchronization with other automata, updating both locations and variable values to reflect a new system state.

First, the methodology section begins by examining preventive and symptomatic protocols, then discusses parameter assumptions and evidence, followed by UPPAAL implementation details and validation. Secondly, the results section presents the average extraction frequency, incidence of complications, and healthcare costs per patient. Thirdly, the conclusion will evaluate model validation, limitations, and future work directions. Finally, the discussion section will point out some model validation, assumptions, limitations and future work directions.

2 METHODOLOGY

2.1 Protocol Definitions

2.1.1 Symptomatic protocol. The symptomatic protocol monitors third molars over time and intervenes only when symptoms develop. Patients receive regular dental examinations, and extraction occurs when clinical indicators warrant intervention.

2.1.2 Preventive protocol. The preventive protocol is based on the KIMO guidelines [2], which provide recommendations for determining when asymptomatic third molars should be preventively removed or left in place.

KIMO advice for preventive extraction:

- **Mandibular jaw:** Impacted third molars with mesial or horizontal angulation, preferably before age 18, when normal

Table 1. Standardized prevalence rates for third molar-related symptoms per 1,000 molars by age group. A dash (-) indicates no data available.

Symptom	Chance per 1,000	
	Younger age (18-30)	Older age (31-80)
Pericoronitis M3	54	140
Periodontal condition M3	-	310
Caries M3	49	307
Periodontal condition M2	197	620
Caries M2	74	320

eruption is unlikely and bone around the crown is absent or partially present, or when deepened pockets exist distal to the second molar.

- **Maxillary jaw:** Non-functional third molars, especially when patient or anatomical factors complicate cleaning, preferably extracted simultaneously with mandibular third molars.

KIMO advice against preventive extraction:

- **Mandibular jaw:** Age above 30 years, completely bone-impacted molars, completely erupted functional molars with good cleaning access, close anatomical relationship between inferior alveolar nerve and roots.
- **Maxillary jaw:** Completely erupted functional molars with good cleaning access, highly impacted molars.

Based on these guidelines, we established that the KIMO guidelines evaluates patients starting at age 17, with subsequent preventive evaluations continuing from ages 18 to 30. However, since most third molars have fully developed their position and angle by age 17 and the clinical assessment criteria remain essentially unchanged throughout this period, we interpreted that the protocol will consider age 17 as the timepoint for preventive third molar extraction.

Given that the KIMO guidelines primarily focus on preventive extraction of mandibular third molars, we consulted with dental experts Dr. Miranda Wetselaar-Glas (Researcher at LUMC, Leiden) and Dr. Peter Wetselaar (Researcher at ACTA, Amsterdam). Based on their advice, we interpreted the preventive protocol in such a way that it will be applied exclusively to mandibular third molars.

Maxillary third molars may be extracted during the same surgical session when mandibular third molars are removed. According to expert estimates, this occurs in approximately 80% of the cases.

The mandibular third molars are evaluated based on their angulation, so when they have mesial or horizontal angulation, they are extracted preventively. Following the evaluation at the age 17, patients with at least one third molar remaining continue under the symptomatic protocol, which monitors third molars during regular visits and extracts them when symptoms develop as defined in the previous section.

2.2 Clinical Parameters

2.2.1 Symptoms. In this model, symptoms are defined as clinical indications requiring third molar extraction. The symptom prevalence has been adopted from KIMO ([2], p16-17), who reviewed seven distinct symptoms across multiple research studies to establish prevalence estimates (detailed in Table 1).

The original prevalence data were reported using inconsistent denominators—some studies used rates per 1,000 molars, while others used rates per 1,000 patients with at least one impacted third molar. To ensure consistency and usability in the model, all prevalence rates were standardized to a per-molar basis. For studies reporting per-patient rates, we applied a transformation that accounts for the fact that each patient can have up to four third molars, making the per-molar risk lower. Specifically, we estimated the probability that a single molar develops symptoms by assuming symptom independence across molars. Taking the fourth root of the probability that a patient has no symptoms approximates the probability that an individual molar remains symptom-free. The per-molar prevalence is then derived by subtracting this value from one:

$$\text{Prevalence per 1,000 molars} = \left[1 - \sqrt[4]{1 - \text{prevalence no symptoms per 1,000 patients}} \right] \times 1,000$$

Following this transformation, we excluded three symptoms from the model due to their extremely low prevalence rates and limited clinical relevance: cysts, tumors, and root resorptions of the second molar. The remaining five symptoms are:

- **Pericoronitis M3:** An inflammation of the gum tissue surrounding a partially erupted third molar, which can lead to pain and infection.
- **Periodontal condition M3:** This refers to the health of the gum tissue around a third molar, which can be affected by factors such as plaque buildup and inflammation.
- **Caries M3:** Third molar decay.
- **Periodontal condition M2:** Inflammation of the gum tissue around a second molar.
- **Caries M2:** Second molar decay.

The standardized prevalence rates for these symptoms are presented in Table 1. These rates represent the probability that any individual third molar will develop each specific symptom over a given time period. The model used these rates to determine when symptoms arise, triggering the need for extraction and associated costs and health outcomes.

2.2.2 Complications. Complications are defined as events that can occur after the extraction of third molars, leading to additional healthcare costs and patient discomfort. The model incorporates the following complications, which are based on the KIMO provided prevalence ([2], p96-97) From these complications, we selected the most relevant ones that are likely to occur after the extraction.

Table 2. Prevalence complications after extracting third molar

Complication	Chance	Risk factor
Pain, swelling, and trismus	20%	Age ≥ 30 (three times higher risk trismus)
Limitations in daily activities	14,3%	-
Alveolitis M3 inferior	8,4%	Age ≥ 30 (two times higher risk)
Infection	2,35%	-
Transient paresthesia of the inferior alveolar nerve	1%	-

Table 3. Costs related to third molar management

Cost type	Costs in euros
Easy extraction	74
Medium difficult extraction with flapping and/or bone removal	99
Difficult extraction with flapping and/or bone removal	149
After care (Problem-oriented consultation)	29

The prevalence rates and risk factors for these complications are summarized in Table 2.

2.2.3 Costs. Costs are an important aspect of the model, as they reflect the financial implications of third molar management protocols. Incorporated costs are:

- **Extraction costs:** The costs associated with the extraction of third molars, which vary based on the complexity of the procedure.
- **Complication costs:** The costs incurred due to complications arising from third molar extractions, including possible painkillers, follow-up treatments, and absenteeism from work or school.

The exact costs were obtained from the Dutch Healthcare Authority [3] and are summarized in Table 3.

2.3 Model Implementation

2.3.1 Model architecture. In order to test the preventive or symptomatic protocol the model has been implemented in UPPAAL. The full XML model and a detailed explanation are available in [6]. The model consists of several components:

- **Global Variables:** System-wide parameters and counters
- **Third molar model:** Individual molar development and management
- **Patient model:** Population-level behavior across age groups
- **Protocol models:** Preventive and symptomatic management strategies

2.3.2 Third molar model. The third molar model (Appendix A, Figure 6) represents the development and management of third molars over time. It includes the angulation, eruption status, symptom development, and complications associated with third molars. The model starts with probabilistically generating the angulation of third molars, which can be mesial (41.17%), horizontal (25.55%), distal (12.17%), or vertical (11.06%) [1]. The eruption status is also determined probabilistically, with the possibility of being fully erupted (5%), partially erupted (80%), or not erupted (5%) [4]. After this, the model generates the symptoms based on the prevalence rates.

The third molar model also includes a representation of the complications that can occur after extraction, such as pain, swelling, trismus, limitations in daily activities, alveolitis M3 inferior, infection, and transient paresthesia of the inferior alveolar nerve. For pain, swelling, trismus (pzt), and alveolitis M3 inferior, the model includes a risk factor based on the age of the patient, where patients aged 30 or older have a higher risk of complications.

2.3.3 Patient model. For the patient model (Appendix A, Figure 7), we assumed that every patient has four third molars. The patient model flows through age groups 17, 18-30, and 31-80 years. The model starts with the initiation of the four third molars, after which the patient can progress through all the age groups, and in every age group, it can check the status of the third molars.

2.3.4 Symptomatic protocol model. The symptomatic protocol model (Appendix A, Figure 8) is designed to manage third molars based on the development of symptoms. The model starts with regular monitoring of third molars during dental visits. If a patient develops symptoms, the protocol will extract the affected third molar. This extraction will incur extraction costs. If it is one of the mandibular third molars, the model will also extract the maxillary third molar with an 80% probability.

2.3.5 Preventive protocol model. The preventive protocol model (Appendix A, Figure 9) is designed to evaluate the third molars based on the KIMO guidelines. The model starts with the evaluation of third molars at age 17, where it checks the angulation and eruption status of the mandibular third molars. If the angulation is mesial or horizontal, the third molar is extracted preventively. If the mandibular third molar is extracted preventively, there is an 80% chance that the maxillary third molar will also be extracted preventively. After this evaluation, the patient continues under the symptomatic protocol, which monitors third molars during regular visits and extracts them when symptoms develop as defined in the previous section.

2.4 Model Validation

To ensure the correctness and reliability of our simulation model, we conducted comprehensive validation testing through formal verification queries. This validation process assessed whether the model's behavior aligns with established clinical protocols and logical expectations. The validation examined five critical aspects of third molar management to verify that the model accurately represents real-world clinical decision-making.

2.4.1 Validation criteria. We established the following validation criteria based on clinical guidelines and expert consensus:

- **Preventive extraction protocol:** Third molars with mesial or horizontal angulation should be identified as high-risk and extracted preventively.
- **Simultaneous maxillary extraction:** When mandibular third molars are extracted, the corresponding maxillary third molars should be removed concurrently in approximately 80% of cases, reflecting standard surgical practice.
- **Age-appropriate symptomatic extraction:** Third molars developing symptoms at younger or older ages should be extracted during the correct age period, ensuring timely therapeutic intervention.
- **Symptoms prevalence:** The model should accurately reflect the prevalence of symptoms based on established clinical data, ensuring that the probability of symptom development aligns with real-world expectations.
- **Complications prevalence:** The model should have the correct prevalence of complications following third molar extraction, incorporating the age risk factor for the complications pain, swelling, trismus, and alveolitis M3 inferior.

2.4.2 Validation results. All verification queries successfully validated the model's behavior against these criteria. The formal verification confirmed that the simulation accurately implements the intended clinical protocols and maintains logical consistency throughout the processes. Complete verification query results and technical details are available in the model repository [6].

Figure 1 shows the probability distribution of preventive extraction for high-risk third molars, demonstrating that these extractions occur exclusively at age 17, which aligns perfectly with the preventive protocol specifications. Figure 2 illustrates the probability distribution of extraction timing for third molars with early-onset symptoms, confirming that these extractions occur between ages 19 and 31. This pattern is clinically correct because symptoms can develop from ages 18 to 30, with extraction occurring in the subsequent year after symptom onset. Finally, Figure 3 demonstrates the probability distribution of extraction timing for third molars with late-onset symptoms, showing extractions occurring from ages 32 to 80. This distribution is appropriate because symptoms can develop from ages 31 to 80, with extraction occurring in the year following symptom development. If symptoms develop at age 80, the model will not extract the third molar at age 81, which is clinically appropriate given the high patient age and associated extraction risks.

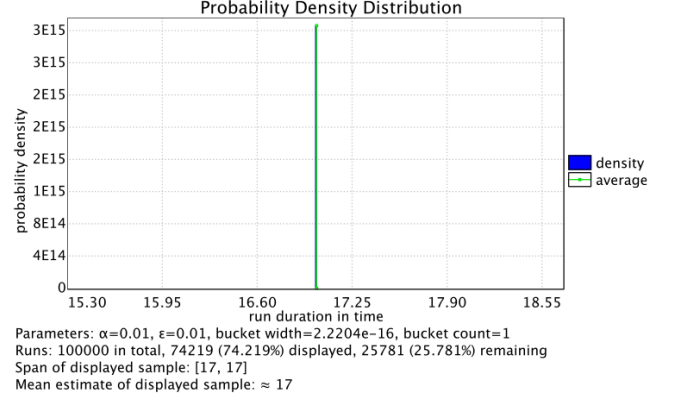


Fig. 1. Probability density distribution of preventive extraction for high-risk third molars with unfavorable angulation

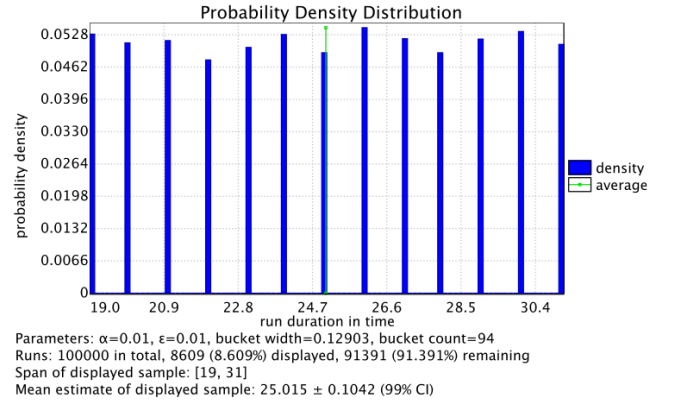


Fig. 2. Probability density distribution of extraction timing for third molars with symptoms at a young age (18-30)

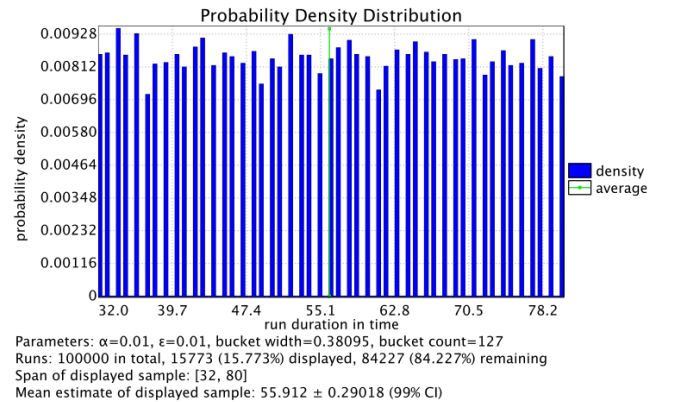


Fig. 3. Probability density distribution of extraction timing for third molars with symptoms at an old age (31-80)

Table 4. Extraction frequency per patient by protocol (e_count: total extractions, se_count: symptomatic extractions, pe_count: preventive extractions, ee_count: extra extractions)

Query	Preventive protocol	Symptomatic protocol
$E[\leq 80; 100,000] (\text{max:e_count})$	$3.95303 \pm 0.0017873 (99\% \text{ CI})$	$3.87756 \pm 0.0028952 (99\% \text{ CI})$
$E[\leq 80; 100,000] (\text{max:se_count})$	$1.07213 \pm 0.00137609 (99\% \text{ CI})$	$3.02717 \pm 0.00573141 (99\% \text{ CI})$
$E[\leq 80; 100,000] (\text{max:pe_count})$	$1.48379 \pm 0.00503794 (99\% \text{ CI})$	≈ 0
$E[\leq 80; 100,000] (\text{max:ee_count})$	$1.39456 \pm 0.00523751 (99\% \text{ CI})$	$0.85176 \pm 0.00560222 (99\% \text{ CI})$

3 RESULTS

We conducted a series of simulations to evaluate the performance of two third molar management protocols. The results are presented in the following sections, which include average extraction frequency, incidence of complications, and healthcare costs per patient. Every query runs 100,000 simulations to ensure statistical reliability. Results are presented with 99% confidence intervals (CI).

3.1 Average Extraction Frequency

To compare extraction frequencies between the two protocols, the average number of extractions per patient across different categories were calculated. The analysis included total extractions, extractions from symptoms, preventive extractions, and additional extractions that could occur when the upper molar is extracted simultaneously with the lower molar (assuming an 80% success rate).

The results and corresponding extraction frequencies are presented in Table 4. The preventive protocol shows slightly higher frequency of extractions (3.95 vs 3.87), primarily due to early preventive interventions. Another notable difference is in the number of additional extractions (simultaneous maxillary extractions), where the preventive protocol has a higher average of 1.39 compared to the symptomatic protocol with approximately 0.85.

3.2 Average Incidence of Complications

To assess the safety profile of each protocol, we analyzed both the average number of complications per patient and the probability of experiencing at least one complication of each type. The results reveal notable differences between the preventive and symptomatic protocols across several complication types.

The overall average number of complications per patient was slightly higher under the preventive protocol (1.64273) compared to the symptomatic protocol (1.63034). However, when complications are disaggregated by type, more pronounced differences emerge.

In particular, the symptomatic protocol exhibited a higher probability of patients experiencing pain, swelling, and trismus (pzt: 0.7586 vs 0.6558) and alveolitis (alv: 0.4203 vs 0.3396). These differences are primarily attributable to an increase in complication risk at older ages. The full results are presented in Table 5.

3.3 Average Healthcare Costs

To evaluate the financial implications of the protocols, simulations were conducted to analyze the costs per patient over time. The cost analysis includes the extraction costs and the costs associated with complications.

Figures 4 and 5 illustrate a simulation results for the preventive and symptomatic protocols, respectively. The simulation with

preventive protocol shows the preventive extraction of four third molars at the age of 17, followed by 4 complications, with the costs staying significantly low.

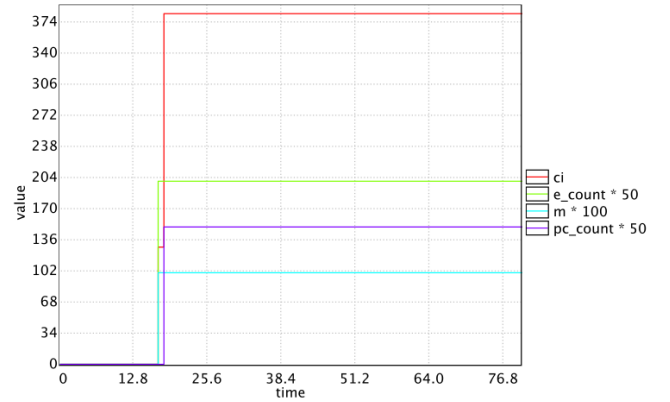


Fig. 4. Preventive model simulation results

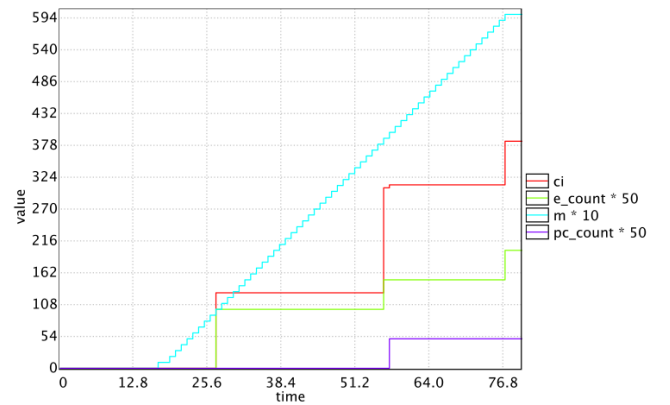


Fig. 5. Symptomatic model simulation results

The cost analysis reveals differences in healthcare costs between the protocols. The preventive protocol resulted in a cost savings (138.704 per patient, 24.6% reduction). From this we see that the preventive protocol leads to fewer extraction procedures and lower

Table 5. Complication incidence per patient by protocol (pc_count: total complications, pzt: pain, swelling, and trismus, bds: limitations in daily activities, alv: alveolitis M3 inferior, inf: infection, par: transient paresthesia of the inferior alveolar nerve)

Query	Preventive protocol	Symptomatic protocol
$E[\leq 80; 100,000]$ (max:pc_count)	1.64273 ± 0.00985267 (99% CI)	1.63034 ± 0.00978232 (99% CI)
$Pr[\leq 80; 100,000]$ (at least one M3 has pzt)	0.655803 ± 0.00387488 (99% CI)	0.758578 ± 0.00349071 (99% CI)
$Pr[\leq 80; 100,000]$ (at least one M3 has bds)	0.455192 ± 0.00406128 (99% CI)	0.448522 ± 0.00405602 (99% CI)
$Pr[\leq 80; 100,000]$ (at least one M3 has alv)	0.339608 ± 0.00386242 (99% CI)	0.420294 ± 0.00402558 (99% CI)
$Pr[\leq 80; 100,000]$ (at least one M3 has inf)	0.0889796 ± 0.00232391 (99% CI)	0.0891196 ± 0.00232555 (99% CI)
$Pr[\leq 80; 100,000]$ (at least one M3 has par)	0.0383621 ± 0.00156912 (99% CI)	0.039432 ± 0.00158991 (99% CI)

Table 6. Average cost of complications per patient by protocol (ci: total costs, ci_pc: patient complication costs)

Query	Preventive protocol	Symptomatic protocol
$E[\leq 80; 100,000]$ (max:ci)	424.044 ± 1.75921 (99% CI)	562.748 ± 1.93255 (99% CI)
$E[\leq 80; 100,000]$ (max:ci_pc)	181.707 ± 1.33795 (99% CI)	201.867 ± 1.60333 (99% CI)

complications costs.

$$\text{Preventive protocol: } \frac{\$181.707}{1.64273} \approx \$110.6 \quad (1)$$

$$\text{Symptomatic protocol: } \frac{\$201.867}{1.63034} \approx \$123.8 \quad (2)$$

Furthermore, the preventive protocol demonstrated a lower ratio of patient complication costs to the average number of complications per patient. The detailed cost analysis is presented in Table 6.

4 CONCLUSIONS

This research demonstrates the effectiveness of using formal modelling with UPPAAL to evaluate third molar management strategies. Through extensive simulations and a formal framework, we compared the preventive protocol and symptomatic protocol on extraction frequency, complications, and healthcare costs.

Answering the first sub-question, we found that the average number of extractions per patient was slightly higher under the preventive protocol (3.95) than under the symptomatic protocol (3.88), an increase of just 1.8%. With the preventive protocol reducing the number of symptomatic extractions by 65% (from 3.02 to 1.07).

For the second sub-question, the average number of complications per patient was marginally higher in the preventive protocol (1.64) compared to the symptomatic one (1.63). However, when normalized by the number of extractions, the complication rates are nearly equivalent. Notably, the symptomatic protocol showed higher rates of severe complications such as pain, swelling, and trismus (75.9% vs 65.6%), and alveolitis (44.8% vs 33.9%). Indicating the increased risk that results from the extraction at an older age. Other complications remain statistically equivalent between the two protocols.

Addressing the third sub-question on healthcare costs, the preventive protocol led to significantly lower average costs per patient (424.044 vs. 562.748), representing a 24.6% reduction. This cost savings stems from the additional extractions that occur in the same operation, and lower complication expenses due to extraction happening at a young age.

Overall, the findings support the preventive protocol as the more effective strategy. Despite a slight increase in extraction frequency, it

substantially reduces long-term healthcare costs and benefits safety outcomes. These results align with current KIMO guidelines, reinforcing the clinical and financial benefits for preventive extraction in third molar management.

5 DISCUSSION

5.1 Model Validation and Limitations

The model requires validation through comparison with real-world clinical data, ideally involving patient outcomes from dental practices that follow similar third molar management protocols. Further expert feedback is also necessary to assess clinical relevance and accuracy. This was planned, however not possible within the project timeframe. Several key limitations affect the model's current validity. The development required assumptions in areas where KIMO guidelines lacked specificity, particularly regarding the prevalence and incidence rates of symptoms and patient complications that lack clinical consensus. Additionally, the model currently assumes all patients have four third molars, whereas many individuals have fewer third molars due to congenital absence or previous extractions.

5.2 Future Work

This research establishes a foundation for enhanced model development in several directions. To refine the modelling assumptions it is necessary to consider in more detail the prevalence and incidence data reported in the literature. The model could be extended to support personalized simulations by incorporating individual-level variables such as age, systemic health conditions, and extended treatments, moving beyond the current patient profile assumptions. The scope of outcome metrics could also be broadened, incorporating patient quality of life, satisfaction, and long-term functional outcomes. This expansion would provide a more comprehensive assessment of third molar management protocol effectiveness and better support clinical decision-making.

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Additionally, I used AI-assisted tools to review and improve the grammar and spelling of this paper.

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A.1 UPPAAL models

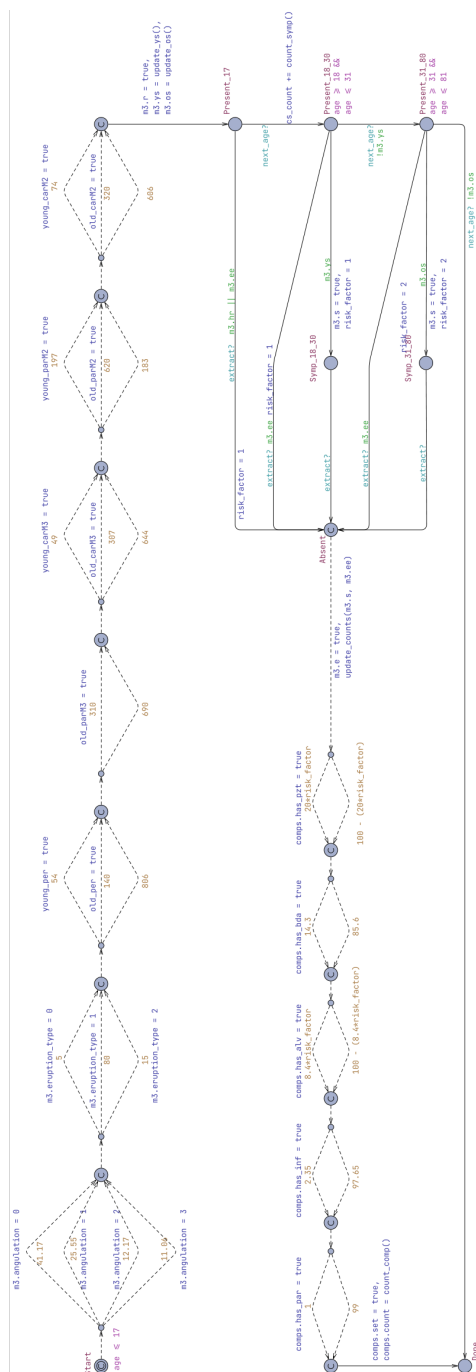


Fig. 6. M3 model

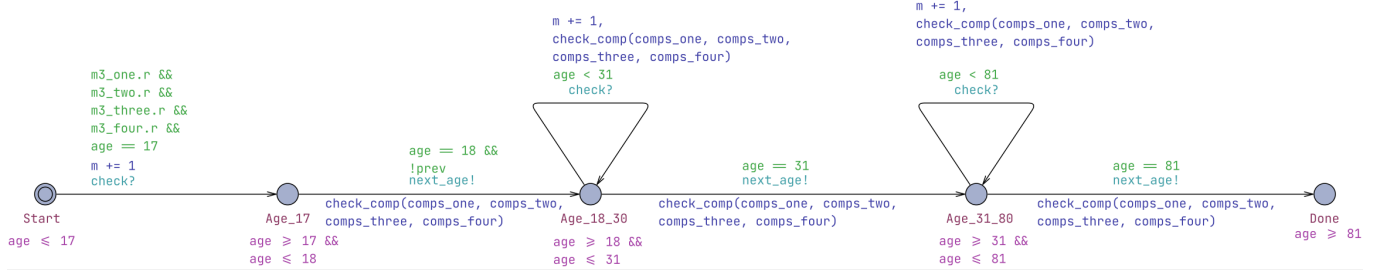


Fig. 7. Patient model

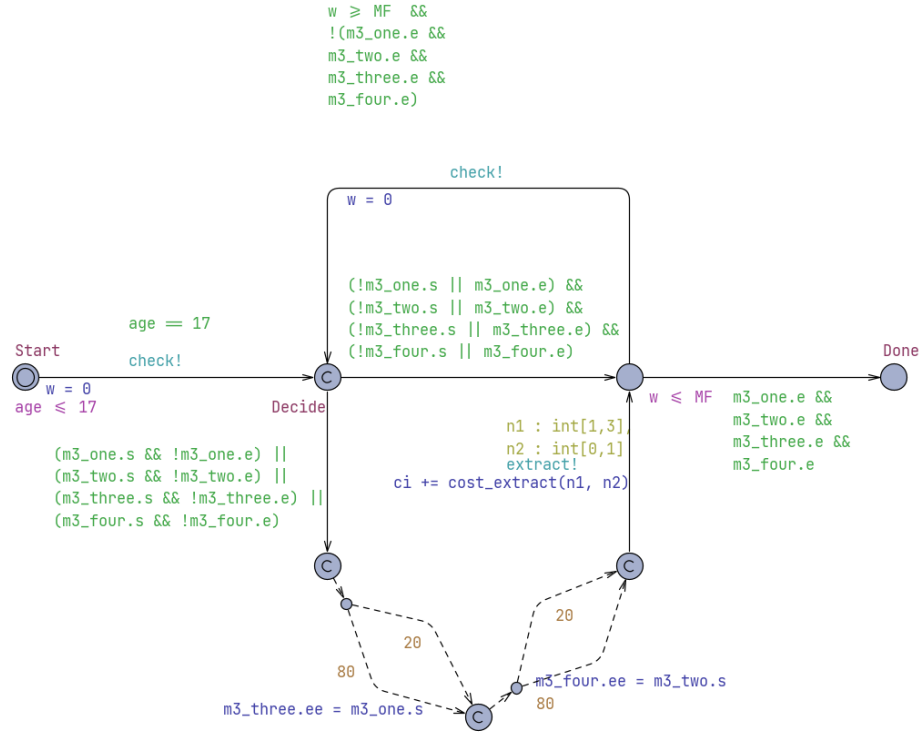


Fig. 8. Symptomatic protocol model

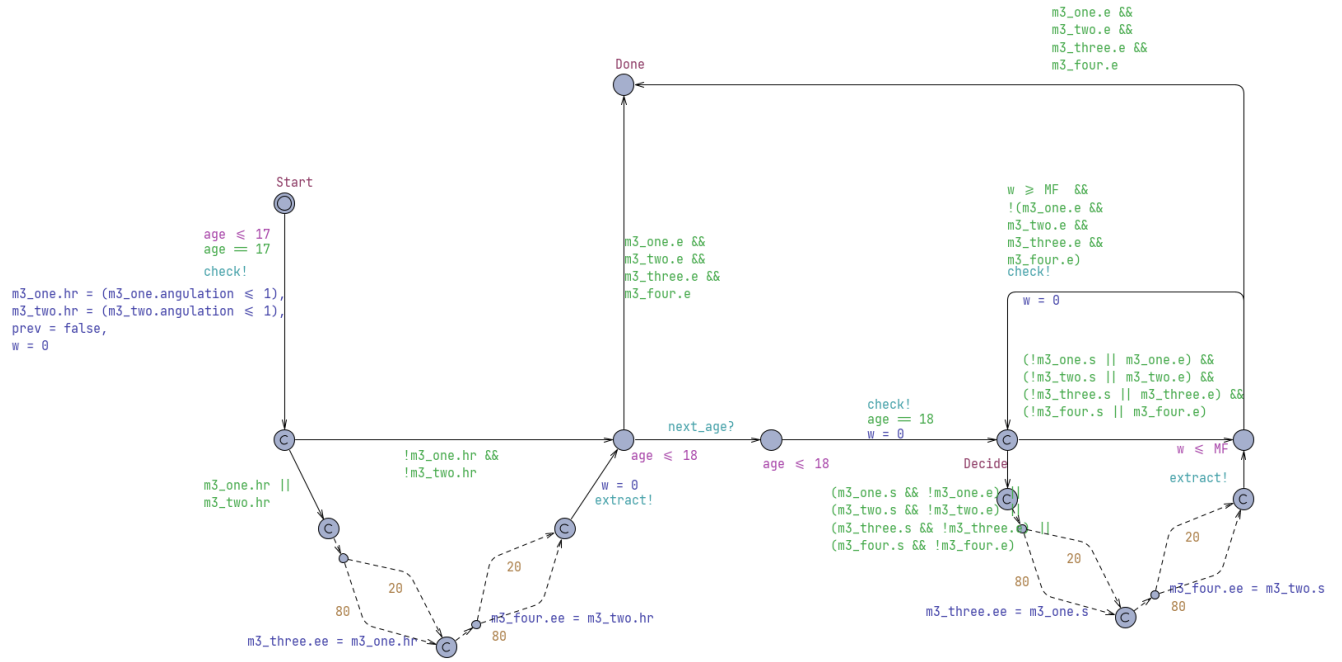


Fig. 9. Preventive protocol model