Modeling Documentation and Instructions for Reproducibility

The Adoption of New Medical Technologies: The Case of Customized Individually Made Knee Implants

Contents:

Section 1: Data

1.1. Time Series

The system dynamics model is designed to project the patient growth rate and the number of patients in 2018 (Section 4) from historical data—patients requiring knee replacement in the U.S. from 1990 to 2012. Furthermore, the estimated model is used to project the trend through 2026.

Table IR1, and Figures IR1 and IR2 present the summary of the number of patients who have had either primary or revision knee replacement surgeries. These datasets are used in the model to replicate the number of patients and estimate the future trends.

Table IR1: Time series data used in the model

Variable	Value	Source
Number of patients undergone primary knee replacement	Figure IR1	Kurtz S., et al. International Survey 2011(1) Kurtz S., et al. 2005 (2) Inacio M., et al. 2017 (3) Bozic et al. (4) Wengler et al. (5)
Number of patients undergone revision knee replacement	Figure IR2	Kurtz S., et al. International Survey 2011 (1) Kurtz S., et al. 2005 (2) Bozic et al. (4) Wengler et al. (5)

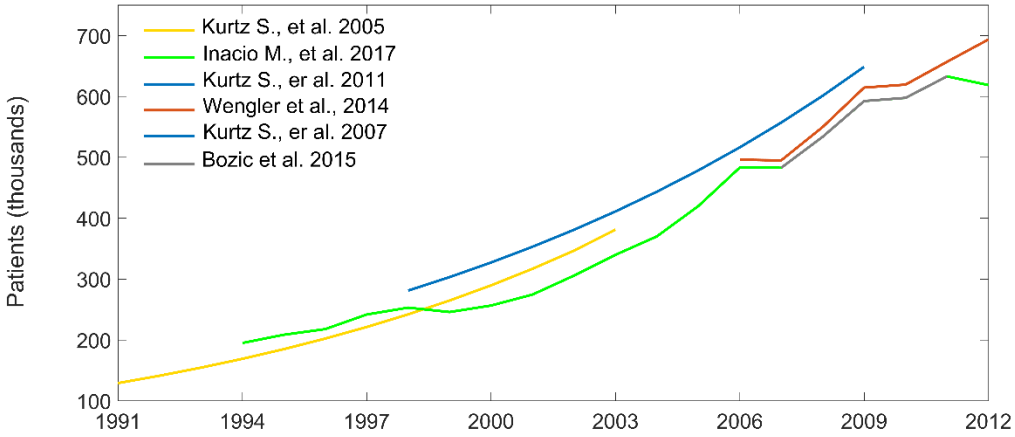


Figure IR1: Total number of patients undergone primary knee replacement in the U.S. from 1990 to 2012.

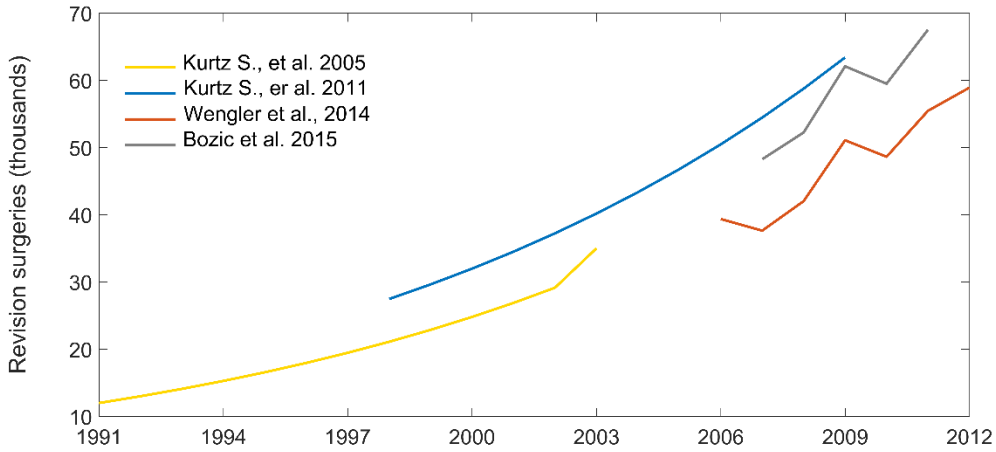


Figure IR2: Total number of patients undergone revision knee replacement in the U.S. from 1990 to 2012.

1.2. Cost

Table IR2 provides details on cost variables used in the model.

Table IR2: Cost variables data used in the model

Variable	Value	Source
Average Cost of Hospital Stay	~$4,000/day	Bill Fay (6) Steven Culler et al.(7)
Cost of Operation Room	~$1500/hr	Derek A. Haas, Robert S. Kaplan (8)
Cost of Surgeon	~$1000/hr	Derek A. Haas, Robert S. Kaplan (8)
OTS Knee Implant Cost*	~$7,000/implant	Robinson J.C. et al. (9)
Cost of Office Visit for Readmitted Patients	~$500/patient	Healthcare bluebook (10)
Cost of Entire Revision Procedure	~$40,000/patient	Healthcare bluebook (10)
Insurance coverage for OTS	0.9	Romualdez I. (11) Lewis S. (12) Greengard S. (13)
Cost of Hospitalization in Rehab or Nursing Facility for Custom	~$8331/patient	Steven Culler et al. (7)
Cost of Hospitalization in Rehab or Nursing Facility for OTS	~$11134/patient	Steven Culler et al. (7)
Cost of Rehabilitation at Home or with Health Care for Custom	~$3776/patient	Steven Culler et al. (7)
Cost of Rehabilitation at Home or with Health Care for OTS	~$3815/patient	Steven Culler et al. (7)

*The cost of OTS implants is according to 2012 price which has probably decreased by about 25%-30%. Since, in our model, the cost of CIM implants is calculated based on OTS price, therefore, that difference in magnitude would not have a significant impact on the results.

Section 2: Model Parameters

Model parameters are constant during the simulation. Table IR3 presents a summary of the parameters, their values, and resources.

Table IR3: Patient Outcome and Time Related Parameters

Parameters	Value	Source
Waiting Time for Surgery	120 Days	Vickiie Oliphant (14)
Initial Number of Patients at first month of 1990	10750	Kurtz, et al. (2)
Initial Number of Patients Used Custom Implants (2016)	50000	Conformis Inc. (15)
Rate of Patients Discharge to Home after OTS Surgery	0.639	Steven Culler et al. (7) John O'Halloran (16) Derek A. Haas, Robert S. Kaplan (8)
Rate of Patients Discharge to Home after CIM Surgery	0.712	Steven Culler et al. (7)
Time to decide on Home Discharges	2 days	American Academy of Orthopaedic Surgeons (17)
Time to Recover Completely after OTS Surgery	4 weeks	Samuel Greengard et al. (18) BoneSmart (19)
Time to Recover Completely after Custom Surgery	2 weeks	Conformis Inc. (2017) (20)
90 Days OTS Readmission Rate	29.2%	Steven Culler et al. (7) William Schairer et al. (21) Nicholas Ramos et al. (22)
90 Days CIM Readmission Rate	17%	Steven Culler et al. (7) William Schairer et al. (21) Nicholas Ramos et al. (22)
3 Year Revision Surgery Rate	5.5%	AJRR (23) NJR (24)
Initial Orthopedic Surgeons Population	8734	AJRR (25)
Net Orthopedic Surgeon Population Increase	2% Increase from 2000-2020	Richard Iorio, et al. (26)
Surgeon to Patient Contact Rate	29 /Month	Mary Rechtoris (27)
Custom Average Hospital Stay	2.97 days	Steven Culler et al. (7)
OTS Average Hospital Stay	3.2 days	Steven Culler et al. (7)
OTS Range of Motion (ROM)	0.71	Ian M. Zeller et al. (28)
OTS Axial Rotation	0.22	Ian M. Zeller et al. (28)
OTS Condyle liftoff (early flexion)	0.357	Ian M. Zeller et al. (28)
OTS Condyle liftoff (late flexion)	0.143	Ian M. Zeller et al. (28)
Custom Range of Motion (ROM)	0.77	Ian M. Zeller et al. (28)
Custom Axial Rotation	0.315	Ian M. Zeller et al. (28)
Custom Condyle liftoff (early flexion)	0	Ian M. Zeller et al. (28)
Custom Condyle liftoff (late flexion)	0.25	Ian M. Zeller et al. (28)

Parameters	Value	Source
Time of OTS Procedure	~2 hrs	Interview (29)
Time reduction during the procedure for Custom	~0.25 hrs	Interview (29)

Section 3: Model Formulation

In this section, the model formulation is presented in the similar format as Vensim software. The equations are listed in two sections as simulation set up and main equations.

Also, the Vensim file can be downloaded from: http://jalali.mit.edu/medical-tech-adoption

3.1. Simulation Set up

1. INITIAL TIME = 0 (Represents the beginning of 2018)
   Unit: Month

2. FINAL TIME = 108 (Represents the end of 2026)
   Unit: Month

3. SAVEPER = TIME STEP
   Unit: Month

4. TIME STEP = 0.0625
   Unit: Month

3.2. Main Equations

5. Total Revision Surgeries=
   Rate of Custom Revision Surgeries in 3 Years + Rate of OTS Revision Surgeries in 3 Years
   Unit: People/Month

6. Readmission ratio=
   Total Readmission/Rate of Incoming Patients
   Unit: Dmnl

7. Revision Surgery ratio=
   Total Revision Surgeries/Rate of Incoming Patients
   Unit: Dmnl

8. Total Readmission=
   Rate of Custom Readmission in 90 days + Rate of OTS Readmission in 90 days
   Unit: People/Month

9. Accumulative Number of Patients Undergone Rev Surgery=
   Custom Patients Undergone Revision Surgery + OTS Patients Undergone Revision Surgery
   Unit: Patients

10. Custom Sales Reps Influence on Surgeons=
    SMOOTH3 (Min (Manufacturer Willingness to Produce Custom, Sales Reps Influence on Promoting OTS), Time for Custom Reps to Adjust)
    Unit: Dmnl
    Comment: Considering the initial value for OTS sales force influence and required time for them to change their interests based on the manufacturers' willingness to produce custom implants. If manufacturers' willingness passes the OTS sales force influence on promoting, then the OTS sales force promoting would change their interests to promote custom implants.

11. Accumulative Number of Patients Readmitted in 90 days after Primary Surgery=
    Custom Patients Readmitted + OTS Patients Readmitted
    Unit: Patients

12. Time savings for Surgeons per Month=
    Custom Patients*Time reduction during the procedure
    Unit: Hour/Month
    Comment: Time can be saved per month for surgeons and hospitals if using custom implants

13. Rate of Incoming Patients=
    Number of Patients Undergo the Surgery at 2017*(Patient Increase Rate + 1)^Time1
    Unit: People/Month
    Comment: Exponential growth for incoming patients

14. Custom total recovery cost rates=
    Custom Cost of Hospital Stay per Month + Custom Cost of Rehab Stay per Month + Custom Cost of Rehabilitation at Home per Month
    Unit: Dollar/Month
    Comment: Total cost of custom recovery per month

15. OTS total recovery cost rates=
    OTS Cost of Hospital Stay per Month + OTS Cost of Rehab Stay per Month + OTS Cost of Rehabilitation at Home per Month
    Unit: Dollar/Month
    Comment: Total cost of OTS recovery per month

16. Patients Deciding on Knee Replacement Method= INTEG (
    Rate of Incoming Patients-Patients Using Custom-Patients Using OTS, Initial Number of Patients at 2017)
    Unit: Patients
    Comment: Dividing incoming patients into two groups (OTS and Custom)

17. OTS Patients=
    Patients Using OTS
    Unit: People/Month

18. Custom Patients=
    Patients Using Custom
    Unit: People/Month

19. Adoption from recommendation=
    Surgeons Recommendation Effectiveness on Surgeons for Custom*Contact with adopters
    Unit: Surgeon/Month
    Comment: It is based on the recommendation effectiveness and contact with the adopters

20. Contact with adopters=
    Probability of Contacts with Adopters*Social contact
    Unit: Surgeon/Month

21. Surgeons Becoming Interested=
    IF THEN ELSE (Switch to Block Custom Surgery=1, Adoption from recommendation * Custom Sales Reps Influence on Surgeons, 0)
    Unit: Surgeon/Month

Comment: To become interested, adoption from recommendation of other surgeons and influence of the sales reps are considered together.

22. Surgeon patient contact=
    Patients Deciding on Knee Replacement Method*Surgeon to Patient Contact Rate*Probability of Contacts with Adopters
    Unit: People/Month

23. Social contact=
    Surgeon to Adopters Contact Rate*Surgeons NOT Willing to Adopt
    Unit: Surgeon/Month

24. Custom Rate of Discharge to home after Rehab=
    Custom Discharged to Rehab or Skilled Nursing Facility/Custom Duration of staying at Rehab
    Unit: People/Month
    Comment: Custom patients going home after rehab recovery

25. OTS Cost of Hospital Stay per Month=
    (OTS Home Recovery Complete + OTS Rate of Discharge to home after Rehab)*Cost of Hospitalization in Hospital for OTS
    Unit: Dollar/Month
    Comment: Cost per month for hospital stay for OTS implant patients

26. OTS Cost of Readmission per Month=
    Price of Office Visit for Readmitted Patients*Rate of OTS Readmission in 90 days
    Unit: Dollar/Month

27. OTS Cost of Rehab Stay per Month=
    Cost of Hospitalization in Rehab or Nursing Facility for OTS*OTS Rate of Discharge to home after Rehab
    Unit: Dollar/Month
    Comment: Cost per month for rehab stay for OTS implant patients

28. OTS Cost of Rehabilitation at Home per Month=
    Cost of Rehabilitation at Home or with Health Care for OTS* OTS Home Recovery Complete
    Unit: Dollar/Month
    Comment: Cost per month for home stay for OTS implant patients

29. OTS Cost of Revision Surgery per Month=
    Cost of Entire Revision Procedure*Rate of OTS Revision Surgeries in 3 Years
    Unit: Dollar/Month

30. Custom Total Cost of the Entire Process=
    Custom Accumulative $ of Readmission + Custom Accumulative $ of Revision + Total Recovery Cost of Custom + Custom Accumulative Cost of Procedures
    Unit: Dollar
    Comment: Total cost including cost of procedure, recovery, readmission, and revision surgery

31. OTS Discharged to Home or Home with Health Care = INTEG (OTS Rate of Discharge to home after Rehab + Rate of OTS Discharge to Home-OTS Home Recovery Complete, 0)
    Unit: Patients

32. OTS Discharged to Rehab or Skilled Nursing Facility = INTEG (

Rate of OTS Discharge to Rehab-OTS Rate of Discharge to home after Rehab, 0)
Unit: Patients

33. Custom Discharged to Home or Home with Health Care = INTEG (Custom Rate of Discharge to home after Rehab + Rate of Custom Discharge to Home-Custom Home Recovery Complete, 0)
Unit: Patients

34. Custom Discharged to Rehab or Skilled Nursing Facility = INTEG (Rate of Custom Discharge to Rehab-Custom Rate of Discharge to home after Rehab, 0)
Unit: Patients

35. Custom Accumulative Cost of Rehab Stay= INTEG (Custom Rehab $, 0)
Unit: Dollar

36. Custom Accumulative Number of Patients= INTEG (Custom Patients, 0)
Unit: People

37. OTS Home $=
OTS Cost of Rehabilitation at Home per Month
Unit: Dollar/Month

38. Total Recovery Cost of OTS=
OTS Accumulative Cost of Hospital Stay + OTS Accumulative Cost of Rehab Stay + OTS Accumulative Cost of Home Recovery
Unit: Dollar
Comment: Total accumulative recovery cost for OTS

39. OTS Hospital $=
OTS Cost of Hospital Stay per Month
Unit: Dollar/Month

40. Percentage of Home Discharge for Custom=
100* XIDZ (Rate of Custom Discharge to Home, Rate of Custom Discharge to Rehab, 0)
Unit: Dmnl

41. Custom Hospital $=
Custom Cost of Hospital Stay per Month
Unit: Dollar/Month
42. OTS Accumulative $ of Readmission= INTEG (OTS Readmission, 0)
Unit: Dollar

43. Custom Accumulative $ of Readmission= INTEG (Custom Readmission, 0)
Unit: Dollar

44. Custom Accumulative $ of Revision= INTEG (Custom Revision, 0)
Unit: Dollar

45. Custom Accumulative cost of Home Recovery= INTEG (Custom Home $, 0)
Unit: Dollar

46. Custom Accumulative Cost of Hospital Stay= INTEG (Custom Hospital $, 0)
Unit: Dollar

47. Custom Accumulative Cost of Procedures=
    Custom Cost of Surgery*(Custom Accumulative Number of Patients) + OTS Product Cost*Multiplication of OTS Product Cost for Price of Custom Implants*(Custom Accumulative Number of Patients)
    Unit: Dollar
    Comment: Total accumulative procedure cost for custom

48. Percentage of Rev Surgery Custom Patients=
    100* XIDZ (Custom Patients Undergone Revision Surgery, Custom Patients Recovering at Home, 0)
    Unit: Dmnl

49. OTS Accumulative Number of Patients= INTEG (OTS Patients, 0)
    Unit: People

50. Probability of Contact with Custom Patients Discharged to Home=
    XIDZ (Custom Patients Recovering at Home, OTS Patients Recovering at Home + Custom Patients Recovering at Home, 0)
    Unit: Dmnl

51. Custom Cost of Rehabilitation at Home per Month=
    Cost of Rehabilitation at Home or with Health Care for Custom*Custom Home Recovery Complete
    Unit: Dollar/Month
    Comment: Cost per month for home stay for custom implant patients

52. OTS Rate of Discharge to home after Rehab=
    OTS Discharged to Rehab or Skilled Nursing Facility/OTS Duration of staying at Rehab
    Unit: People/Month
    Comment: OTS patients going home after rehab recovery

53. OTS Readmission=
    OTS Cost of Readmission per Month
    Unit: Dollar/Month
54. OTS Rehab $=
    OTS Cost of Rehab Stay per Month
    Unit: Dollar/Month

55. Custom Cost of Hospital Stay per Month=
    (Custom Home Recovery Complete + Custom Rate of Discharge to home after Rehab)*Cost of Hospitalization in Hospital for Custom
    Unit: Dollar/Month
    Comment: Cost per month for hospital stay for custom implant patients

56. Custom Cost of Readmission per Month=
    Price of Office Visit for Readmitted Patients*Rate of Custom Readmission in 90 days
    Unit: Dollar/Month

57. Custom Cost of Rehab Stay per Month=
    Cost of Hospitalization in Rehab or Nursing Facility for Custom*Custom Rate of Discharge to home after Rehab
    Unit: Dollar/Month
    Comment: Cost per month for rehab stay for custom implant patients

58. Custom Cost of Revision Surgery per Month=

Multiplication of OTS Rev Surgery Price*Cost of Entire Revision Procedure*Rate of Custom Revision Surgeries in 3 Years
Unit: Dollar/Month

59. Percentage of Rev Surgery OTS Patients=
100* XIDZ (OTS Patients Undergone Revision Surgery, OTS Patients Recovering at Home, 0)
Unit: Dmnl

60. OTS Accumulative Cost of Rehab Stay= INTEG (OTS Rehab $, 0)
Unit: Dollar

61. Custom Revision=
Custom Cost of Revision Surgery per Month
Unit: Dollar/Month

62. Total Recovery Cost of Custom=
Custom Accumulative Cost of Hospital Stay + Custom Accumulative Cost of Rehab Stay + Custom Accumulative cost of Home Recovery
Unit: Dollar
Comment: Total accumulative recovery cost for custom

63. Insurance Coverage of Total Cost for Custom=
Custom Total Cost of the Entire Process* Coverage of Insurance Bundled Payments for CIM
Unit: Dollar

64. OTS Accumulative Cost of Hospital Stay= INTEG (OTS Hospital $, 0)
Unit: Dollar

65. Custom Home $=
Custom Cost of Rehabilitation at Home per Month
Unit: Dollar/Month

66. Custom Readmission=
Custom Cost of Readmission per Month
Unit: Dollar/Month

67. Custom Rehab $=
Custom Cost of Rehab Stay per Month
Unit: Dollar/Month

68. Insurance Coverage of Total Cost for OTS=
Insurance Coverage for OTS*OTS Total Cost of the Entire Process
Unit: Dollar

69. OTS Accumulative $ of Revision= INTEG (OTS Revision, 0)
Unit: Dollar

70. Percentage of Home Discharge for OTS=
100* XIDZ (Rate of OTS Discharge to Home, Rate of OTS Discharge to Rehab, 0)
Unit: Dmnl

71. Percentage of Readmitted Custom Patients=
100* XIDZ (Custom Patients Readmitted, Custom Patients Recovering at Home, 0)

Unit: Dmnl

72. OTS Accumulative Cost of Procedures=
(OTS Accumulative Number of Patients)*(OTS Cost of Surgery + OTS Product Cost)
Unit: Dollar
Comment: Total accumulative procedure cost for OTS

73. OTS Accumulative Cost of Home Recovery= INTEG (OTS Home $, 0)
Unit: Dollar

74. OTS Revision=
OTS Cost of Revision Surgery per Month
Unit: Dollar/Month

75. Percentage of Readmitted OTS Patients=
100* XIDZ (OTS Patients Readmitted, OTS Patients Recovering at Home, 0)
Unit: Dmnl

76. OTS Total Cost of the Entire Process=
OTS Accumulative $ of Readmission + OTS Accumulative $ of Revision + Total Recovery Cost of OTS + OTS Accumulative Cost of Procedures
Unit: Dollar
Comment: Total cost including cost of procedure, recovery, readmission, and revision surgery

77. Custom Home Recovery Complete=
Custom Discharged to Home or with Home Health Care/Custom Duration of Recovery at Home
Unit: Implants/Month

78. Initial OTS Performance=
OTS Functioning*(1-OTS Liftoff)
Unit: Dmnl
Comment: Implant liftoff has negative impact on performance

79. OTS Learning Curve Strength=
LN (1+OTS Performance Improvement per Doubling of Cooperation)/LN(2)
Unit: Dmnl
Comment: Learning curve formulation, John D. Sterman, Business Dynamics (2000), Chapter 9

80. Effect of Coop on OTS Performance=
(Surgeon and Mfg Coop on OTS/Initial Number of OTS Implants)^OTS Learning Curve Strength
Unit: Dmnl
Comment: Learning curve formulation, John D. Sterman, Business Dynamics (2000), Chapter 9

81. OTS Duration of Recovery at Home=
Time to Recover Completely after OTS Surgery*Effect of OTS performance on Recovery
Unit: Month
Comment: Effect of implant performance is considered for home recovery

82. OTS Duration of staying at Rehab=
OTS Average Rehab Stay*Effect of OTS performance on Recovery
Unit: Month
Comment: Effect of implant performance is considered for rehab recovery

83. Effect of OTS performance on Recovery=
1-(OTS Performance-Initial OTS Performance)
Unit: Dmnl

84. OTS Home Recovery Complete=
OTS Discharged to Home or with Home Health Care/OTS Duration of Recovery at Home
Unit: Implants/Month

85. Surgeon and Mfg Coop on OTS= INTEG (OTS Purchase Rate, Initial Number of OTS Implants)
Unit: Implants

86. Custom Duration of Recovery at Home=
Time to Recover Completely after Custom Surgery*Effect of Custom performance on Recovery
Unit: Month
Comment: Effect of implant performance is considered for home recovery

87. OTS Patient Outcome=
SMOOTH3 (OTS Performance, Total Duration of OTS Recovery)
Unit: Dmnl
Comment: OTS patient outcome considering the duration of recovery

88. Custom Duration of staying at Rehab=
Custom Average Rehab Stay*Effect of Custom performance on Recovery
Unit: Month
Comment: Effect of implant performance is considered for rehab recovery

89. OTS Purchase Rate=
Patients Using OTS
Unit: People/Month

90. Custom Performance=
Min ((Initial Custom Performance) * Switch for Experience Effect on Performance*Effect of Cooperation on Custom Implant Performance+ (Initial Custom Performance) * (1-Switch for Experience Effect on Performance)*Effect of Cooperation on Custom Implant Performance, 1)
Unit: Dmnl
Comment: Implant performance considering the initial performance and improvement in the performance due to the cooperation of manufacturers and surgeons

91. Initial Custom Performance=
Custom Functioning*(1-Custom Liftoff)
Unit: Dmnl
Comment: Implant liftoff has negative impact on performance

92. OTS Performance=
Min ((Initial OTS Performance * Effect of Coop on OTS Performance), 1)
Unit: Dmnl
Comment: Implant performance considering the initial performance and improvement in the performance due to the cooperation of manufacturers and surgeons

93. Effect of Custom performance on Recovery=
1-(Custom Performance-Initial Custom Performance)
Unit: Dmnl

94. Effect of Cooperation on Custom Implant Performance=
(Surgeon and Mfg Cooperation on CIM/Initial Number of Custom Implants)^Learning Curve Strength
Unit: Dmnl
Comment: Learning curve formulation, John D. Sterman, Business Dynamics (2000), Chapter 9

95. Surgeon and Mfg Cooperation on CIM= INTEG (Custom Purchase Rate, Initial Number of Custom Implants)
Unit: Implants

96. Surgeon Adoption Ratio=
Surgeon Adopters/Total Orthopedic Surgeon Population
Unit: Dmnl

97. Rate of OTS Discharge to Rehab =
Patients Undergoing OTS Implant*(1-Rate of patients discharge to home after OTS surgery)/Time to Decide on Home Discharges
Unit: Implants/Month
Comment: Rate of patients discharge to either rehab or nursing facility after OTS surgery

98. Time to Decide on Home Discharge from Rehab=
Custom Average Rehab Stay
Unit: Month

99. Rate of OTS Discharge to Home=
Patients Undergoing OTS Implant*Rate of patients discharge to home after OTS surgery/Time to Decide on Home Discharges
Unit: Implants/Month
Comment: Rate of patients discharge to either home or home with health care after OTS surgery

100. Time to Decide on Home Discharge from OTS Rehab=
OTS Average Rehab Stay
Unit: Month

101. Number of Patients Adopting Custom from Surgeons Recommendation=
SMOOTH3 (Surgeon patient contact * Surgeons Recommendation Effectiveness on Patients for Custom, Time to make a decision)
Unit: Implants/Month
Comment: Surgeons recommendation effectiveness and surgeon patient contact rate are two driving factors for patients to adopt the new product from surgeons recommendation

102. Manufacturer Willingness to Produce Custom=
DELAY3 (Ratio of Patient Using Custom, Delay for Manufacturers to React to the Market Share to Adopt the new Technology)
Unit: Dmnl
Comment: Fragmented industry/market is a market that none of the players have enough share to dominate the market. Meaning no major player controlling everything. By increase in the number of patients using custom implants, more manufacturers willing to produce custom after associated time delay

103. Ratio of Patient Using Custom= ACTIVE INITIAL (XIDZ (Patients Using Custom, Patients Using OTS + Patients Using Custom, 0), 0.05)
Unit: Dmnl

104. Percentage of Readmitted OTS Patients to all Readmitted Patients=
100*XIDZ (OTS Patients Readmitted, Custom Patients Readmitted + OTS Patients Readmitted, 0)
Unit: Dmnl

105. Percentage of OTS Patients Undergone Revision Surgery to all Revision Surgeries=
100*XIDZ (OTS Patients Undergone Revision Surgery, Custom Patients Undergone Revision Surgery +OTS Patients Undergone Revision Surgery, 0)
Unit: Dmnl

106. Percentage of Patients Using Custom=
XIDZ (100*Patients Using Custom, Rate of Incoming Patients, 0)
Unit: Dmnl

107. Percentage of Patients Using OTS=
XIDZ (100*Patients Using OTS, Rate of Incoming Patients, 0)
Unit: Dmnl

108. Rate of Reverting Back to OTS=
IF THEN ELSE (Custom Patient Outcome>OTS Patient Outcome, 0, Surgeon Adopters*(1-Relative Performance of Custom over OTS))/Time to Revert
Unit: Surgeon/Month
Comment: If custom patient outcome is smaller than the OTS patient outcome then larger rate of the surgeons who adopt custom implants before would revert back to OTS.

109. Surgeons Adoption Rate=
IF THEN ELSE (Coverage of Insurance Bundled Payments for CIM>= Insurance Coverage for OTS, Potential Surgeons Adopters * Relative Performance of Custom over OTS, Coverage of Insurance Bundled Payments for CIM * Potential Surgeons Adopters * Relative Performance of Custom over OTS)/Time to make a decision
Unit: Surgeon/Month
Comment: Insurance policies are one of the driving factors for surgeons to become adopters of the new product. In this case if the insurance coverage for custom becomes equal or greater than the coverage for OTS then surgeons would adopt the new product easier. If the insurance coverage for custom is smaller than the coverage for OTS, then that would impact the surgeons' adoption. Another driving factor is the relative performance of the new product which would impact the surgeons' decision on adopting the new product.

110. Custom Purchase Rate=
Patients Using Custom
Unit: Implants/Month

111. Total Cost of the Entire System for Both Methods=
Custom Total Cost of the Entire Process + OTS Total Cost of the Entire Process
Unit: Dollar

112. Custom RAR=
Readmission Rate*(1-Custom Patient Outcome)
Unit: Dmnl
Comment: Readmission Rate (RAR) is based on the rate from literature and patient outcome in such a way if the outcome of patients improves RAR would decrease

113. Custom RSR=

Revision Surgery Rate*(1-Custom Patient Outcome)
Unit: Dmnl
Comment: Revision Surgery Rate (RSR) is based on the rate from literature and patient outcome in such a way if the outcome of patients improves RSR would decrease

114. Patients Using Custom=
DELAY3 (Rate of Incoming Patients*Fraction of Patients Willing to Use Custom, Waiting time)
Unit: Implants/Month
Comment: Rate of patients undergo custom surgery including waiting time delay

115. Patients Using OTS=
DELAY3 (Rate of Incoming Patients*(1-Fraction of Patients Willing to Use Custom), Waiting time)
Unit: Implants/Month
Comment: Rate of patients undergo OTS surgery including waiting time delay

116. Fraction of Patients Willing to Adopt Custom=
XIDZ (Number of Patients willing to adopt Custom, Number of Patients in Waiting List for Knee Replacement + Number of Patients willing to adopt Custom, 0)
Unit: Dmnl
Comment: Relative ratio of patients willing to adopt custom implants to patients in the waiting list for knee replacement

117. Number of Patients in Waiting List for Knee Replacement=
Patients Deciding on Knee Replacement Method/Waiting time
Unit: Implants/Month

118. Fraction of Patients Willing to Use Custom= ACTIVE INITIAL (IF THEN ELSE (Switch to Block Custom Surgery=1, Coverage of Insurance Bundled Payments for CIM*Fraction of Patients Willing to Adopt Custom, 0), 0.05)
Unit: Dmnl
Comment: Fraction of patients willing to adopt custom decide to undergo custom implants surgery based on the insurance policy to cover custom implants

119. Learning Curve Strength=
LN (1+Custom Performance Improvement per Doubling of Cooperation)/LN(2)
Unit: Dmnl
Comment: Learning curve formulation, John D. Sterman, Business Dynamics (2000), Chapter 9

120. Custom Patient Outcome=
SMOOTH3 (Custom Performance, Total Duration of Custom Recovery)
Unit: Dmnl
Comment: Custom patient outcome considering the duration of recovery

121. OTS Liftoff=
(OTS Condyle liftoff in early flexion+ OTS Condyle liftoff in late flexion)/2
Unit: Dmnl
Comment: Average of early flexion and late flexion liftoff

122. OTS Functioning =
(OTS Range of Motion + OTS Axial Rotation)/2
Unit: Dmnl
Comment: Average of the range of motion and axial rotation

123. Custom Functioning=
(Custom Range of Motion + Custom Axial Rotation)/2
Unit: Dmnl
Comment: Average of the range of motion and axial rotation

124. Custom Liftoff=
(Custom Condyle liftoff in early flexion+ Custom Condyle liftoff in late flexion)/2
Unit: Dmnl
Comment: Average of early flexion and late flexion liftoff

125. Rate of OTS Revision Surgeries in 3 Years =
DELAY3 (Patients Using OTS*OTS RSR, "3 Year Time period")
Unit: Implants/Month

126. Rate of Custom Revision Surgeries in 3 Years=
DELAY3 (Patients Using Custom*Custom RSR, "3 Year Time period")
Unit: Implants/Month

127. Rate of Custom Readmission in 90 days=
DELAY3 (Patients Using Custom*Custom RAR, "90 Days Time Period")
Unit: Implants/Month

128. Rate of OTS Readmission in 90 days=
DELAY3 (Patients Using OTS*OTS RAR,"90 Days Time Period")
Unit: Implants/Month
129. OTS RAR=
(1-OTS Patient Outcome)*Readmission Rate
Unit: Dmnl
Comment: Readmission Rate (RAR) is based on the rate from literature and patient outcome in such a way if the outcome of patients improves RAR would decrease

130. OTS RSR=
Revision Surgery Rate*(1-OTS Patient Outcome)
Unit: Dmnl
Comment: Revision Surgery Rate (RSR) is based on the rate from literature and patient outcome in such a way if the outcome of patients improves RSR would decrease

131. Patients Undergoing Custom Implant= INTEG (Patients Using Custom-Rate of Custom Discharge to Home-Rate of Custom Discharge to Rehab, 0)
Unit: Patients
Comment: Patients undergo custom surgery

132. Patients Undergoing OTS Implant= INTEG (Patients Using OTS-Rate of OTS Discharge to Home-Rate of OTS Discharge to Rehab, 0)
Unit: Patients
Comment: Patients undergo OTS surgery

133. Rate of Custom Discharge to Rehab=
Patients Undergoing Custom Implant*(1-Rate of patients discharge to home after Custom Surgery)/Time to Decide on Home Discharges
Unit: Implants/Month
Comment: Rate of patients discharge to either rehab or skilled nursing facility after custom surgery

134. Rate of Custom Discharge to Home=
Patients Undergoing Custom Implant*Rate of patients discharge to home after Custom Surgery/Time to Decide on Home Discharges
Unit: Implants/Month
Comment: Rate of patients discharge to either home or home with health care after custom surgery

135. OTS Patients Undergone Revision Surgery= INTEG (Rate of OTS Revision Surgeries in 3 Years, 0)
Unit: Patients

136. Custom Patients Undergone Revision Surgery= INTEG (Rate of Custom Revision Surgeries in 3 Years, 0)
Unit: Patients

137. Custom Patients Readmitted= INTEG (Rate of Custom Readmission in 90 days, 0)
Unit: Patients

138. OTS Patients Readmitted= INTEG (Rate of OTS Readmission in 90 days, 0)
Unit: Patients

139. Cost of recovery for Custom per Patient=
DELAY1 (Cost of Hospitalization in Hospital for Custom + Cost of Hospitalization in Rehab or Nursing Facility for Custom + Cost of Rehabilitation at Home or with Health Care for Custom, Total Duration of Custom Recovery)
Unit: Dollar/Patients
Comment: Total cost per patient for custom implant recovery

140. Cost of Recovery for OTS per Patient=
DELAY1 (Cost of Hospitalization in Hospital for OTS + Cost of Hospitalization in Rehab or Nursing Facility for OTS + Cost of Rehabilitation at Home or with Health Care for OTS, Total Duration of OTS Recovery)
Unit: Dollar/Patients
Comment: Total cost per patient for OTS implant recovery

141. Initial Early Adopters= INITIAL(Total Orthopedic Surgeon Population *Fraction of Surgeons willing to adopt)
Unit: Surgeon

142. Surgeon Adopters= INTEG (Surgeons Adoption Rate-Rate of Reverting Back to OTS, Initial Early Adopters)
Unit: Surgeon

143. Total Orthopedic Surgeon Population=
(1+Net Orthopedic Surgeon Population Increase)*Initial Orthopedic Surgeon Population
Unit: Surgeon

144. Probability of Contacts with Adopters=
Surgeon Adopters/Total Orthopedic Surgeon Population
Unit: Dmnl

145. Surgeons NOT Willing to Adopt= INTEG (Rate of Reverting Back to OTS + Surgeons Not Interested-Surgeons Becoming Interested,
Initial surgeons NOT willing to adopt)
Unit: Surgeon

146. Potential Surgeons Adopters= INTEG (Surgeons Becoming Interested-Surgeons Not Interested-Surgeons Adoption Rate, 0)
Unit: Surgeon

147. Initial surgeons NOT willing to adopt = INITIAL(
Total Orthopedic Surgeon Population*(1-Fraction of Surgeons willing to adopt))
Unit: Surgeon

148. Surgeons Not Interested=
(1-Relative Performance of Custom over OTS)*Potential Surgeons Adopters/Time to make a decision
Unit: Surgeon/Month
Comment: Surgeons not interested in using custom implants due to the relative performance of the implants over the decision time

149. Relative Performance of Custom over OTS=
Custom Patient Outcome/ (Custom Patient Outcome + OTS Patient Outcome)
Unit: Dmnl

150. Social Awareness=
Patient to Patient Contact Rate*(Custom Patients Recovering at Home)
Unit: Implants/Month

151. Number of Patients Adopting Custom from General Awareness=
Patients Becoming Interested in Custom*Adoption Fraction
Unit: Implants/Month

152. Number of Patients willing to adopt Custom=
Number of Patients Adopting Custom from General Awareness + Number of Patients Adopting Custom from Surgeons Recommendation
Unit: Patients/Month
Comment: Total number of patients willing to adopt due to social awareness and surgeons' recommendation

153. Custom Patients Recovering at Home= INTEG (Custom Home Recovery Complete, 0)
Unit: Patients

154. OTS Duration of Hospitalization=
OTS Average Hospital Stay
Unit: Month

155. Custom Duration of Hospitalization=
Custom Average Hospital Stay
Unit: Month

156. OTS Patients Recovering at Home= INTEG (OTS Home Recovery Complete, 0)
Unit: Patients

157. Total Duration of OTS Recovery=
OTS Duration of Hospitalization + OTS Duration of Recovery at Home + OTS Duration of staying at Rehab
Unit: Month

158. Cost of Hospitalization in Hospital for OTS=
Average Cost of Hospital Stay*OTS Duration of Hospitalization
Unit: Dollar/Patients
Comment: Cost per patient for hospital stay for OTS implant patients

159. OTS Cost of Surgery=
(Cost of Surgeon + Cost of Operations Room)*Time of OTS Procedure
Unit: Dollar/Patients
Comment: Cost of surgery includes cost of surgeon, cost of operation room and time of the procedure

160. Time of Custom Procedure=
Time of OTS Procedure-Time reduction during the procedure
Unit: Hour/Patients

161. Custom Cost of Surgery=
(Cost of Operations Room + Cost of Surgeon)*Time of Custom Procedure
Unit: Dollar/Patients
Comment: Cost of surgery includes cost of surgeon, cost of operation room and time of the procedure

162. Total Duration of Custom Recovery=
(Custom Duration of Hospitalization + Custom Duration of Recovery at Home + Custom Duration of staying at Rehab)
Unit: Month

163. Cost of Hospitalization in Hospital for Custom=
Average Cost of Hospital Stay*Custom Duration of Hospitalization
Unit: Dollar/Patients
Comment: Cost per patient for hospital stay for custom implant patients

164. Patients Becoming Interested in Custom=
Probability of Contact with Custom Patients Discharged to Home*Social Awareness
Unit: Implants/Month
Comment: Patients becoming interested in custom implants by having contact with patients who previously underwent the custom implant surgery

Section 4: Model Calibration and Validation

While many of the model parameters are obtained from various existing datasets, there are no comprehensive data available for some parameters. In this situation, calibrating the model statistically to data would be a helpful method to estimate the unknown parameters. To do so, partial model calibration method (30) is used to calibrate different parts of the model separately. This method decreases the overfitting chances by providing robust estimates.

For some of the unknown parameters, calibration cannot be done; thus, several assumptions have been made based on empirical knowledge. Therefore, conducting sensitivity analysis is essential to test the sensitivity of the model to our assumptions.

4.1. Unknown Parameters Calibration

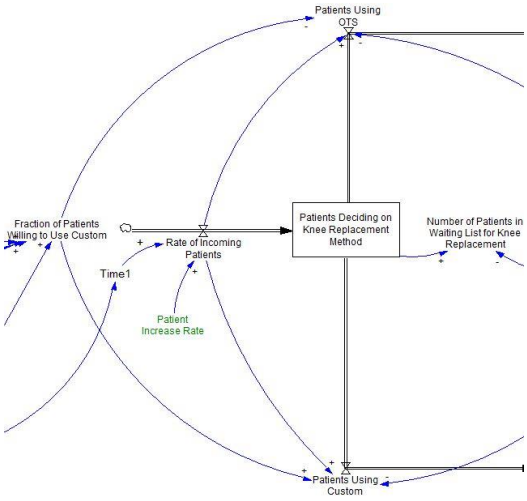
Table IR4 provides information on the calibrated model parameters.

Table IR4: Estimated Model Parameters

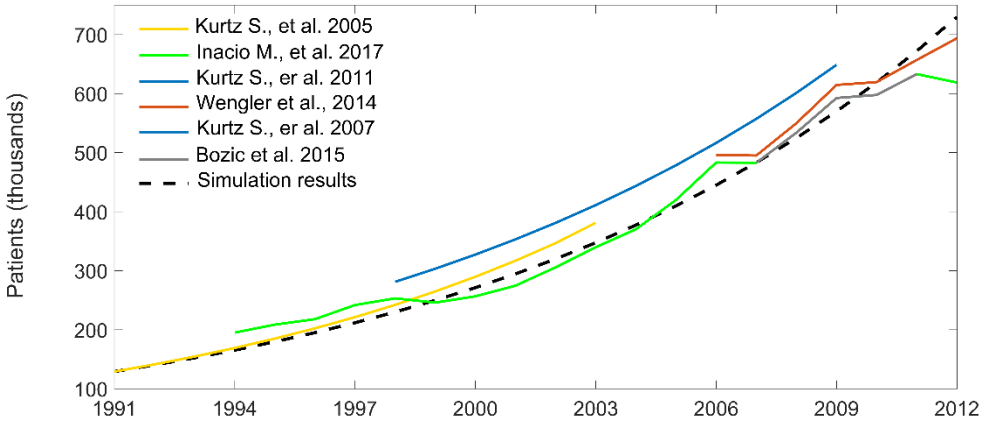
Parameters	Value	Calibration
Patient Increase Rate	0.0069	Calibration 1
Revision Surgery Rate	0.0875	Calibration 2

4.1.2. Calibration 1

- **Input:** Rate of incoming patients based on the historical data from different resources on Number of patients undergone primary knee replacement presented in Table IR1 (Section 1).
- **Payoff function:** Maximize the fit between the historical data and the simulation of patients decided to have knee replacement.
- **Result:** Finding the unknown parameter, Patient Increase Rate (Table IR4).



a) Sub-Model Structure (Estimated parameter is in green)

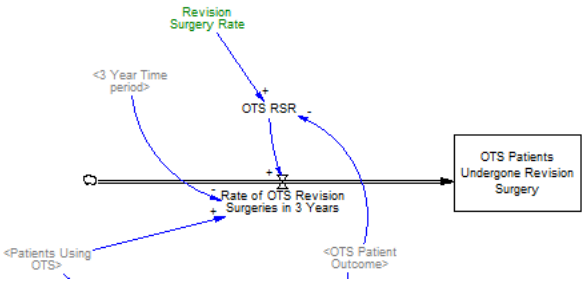


b) Simulated Outcomes

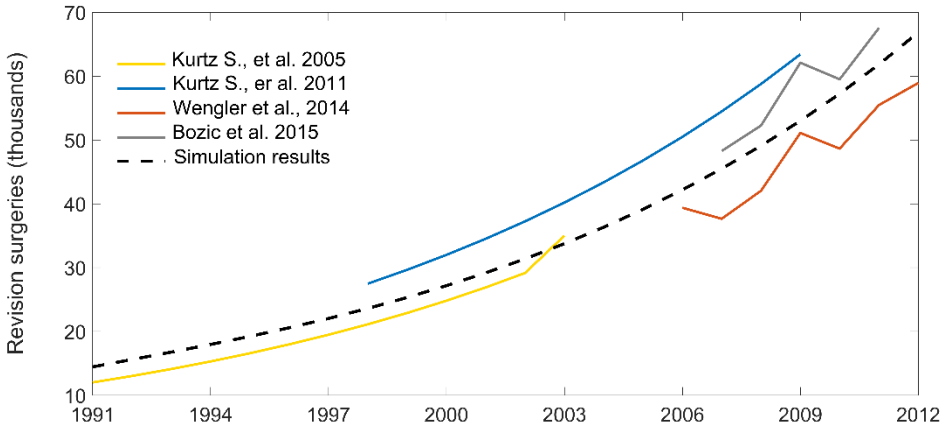
Figure IR3: Calibration 1, containing: **a)** sub-model structure, **b)** simulated outcome

4.1.3. Calibration 2

- **Input:** Rate of OTS revision surgeries in 3 years after primary knee replacement. Data is available from different resources on Number of patients undergone revision knee replacement presented in Table IR1 (Section 1).
- **Payoff function:** Maximize the fit between the historical data and the simulation of patients undergone revision procedures.
- **Result:** Finding the unknown parameter, Revision Surgery Rate (Table IR4).



a) Sub-Model Structure (Estimated parameter is in green)



a) Simulated Outcomes

Figure IR4: Calibration 2, containing: **a)** sub-model structure, **b)** simulated outcome

4.2. Unknown Parameter Assumptions

Table IR5 provides information on the parameter assumptions. Sensitivity analysis on some of the assumptions is provided in the Supporting Information (section 3).

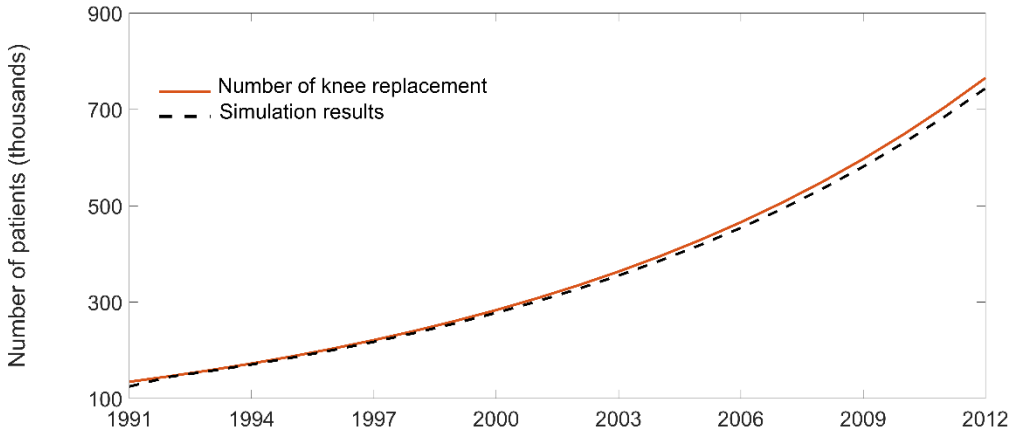
Table IR5: Assumptions on Time Related and Model Parameters

Parameters	Value	Definition
Number of Patients Undergo Primary TKA at first month of 2017	110760	Estimated number of patients at 2017 by Kurtz S., et al. (1)
OTS Average Rehab Stay	4 Days	Rehab stay for patients with OTS implants is between 2 to 7 days. Assumed 4 days.
Custom Average Rehab Stay	3 Days	Rehab stay for patients with Custom implants is between 2 to 5 days. Assumed 3 days.
Surgeons Recommendation Effectiveness on other Surgeons for Custom Implants	30%	Presents the effectiveness of recommendation of early adopter surgeons on the surgeons who are becoming interested in using custom implants.
Fraction of Surgeons willing to Adopt Custom (Early Adopters)	1%	The number of early adopter surgeons assumed as 1% of total surgeons population (<300).
Surgeons to Adopters (Surgeons) Contact Rate	10/Month	It is assumed each surgeon has contact with 10 adopter surgeons each month.
Time to Adopt Custom (for Surgeons)	1 year	Presents the time period takes for a surgeons to be convinced and adopt the new technology after comparing patient outcome of the old and new products.
Time to Revert (from Custom for Surgeons)	6 months	Presents the time period takes for adopter surgeons to revert to the old product when they don't see any improvements in patient outcome.
Time for Custom Reps to Adjust (their interests)	3 months	Presents the time takes for sales force to switch to promote new product after manufacturers turned their interests.
Surgeons Recommendation Effectiveness on Patients for Custom Implants	80%	Presents the effectiveness of recommendation of surgeons on their patients who are going to have knee replacement procedure.

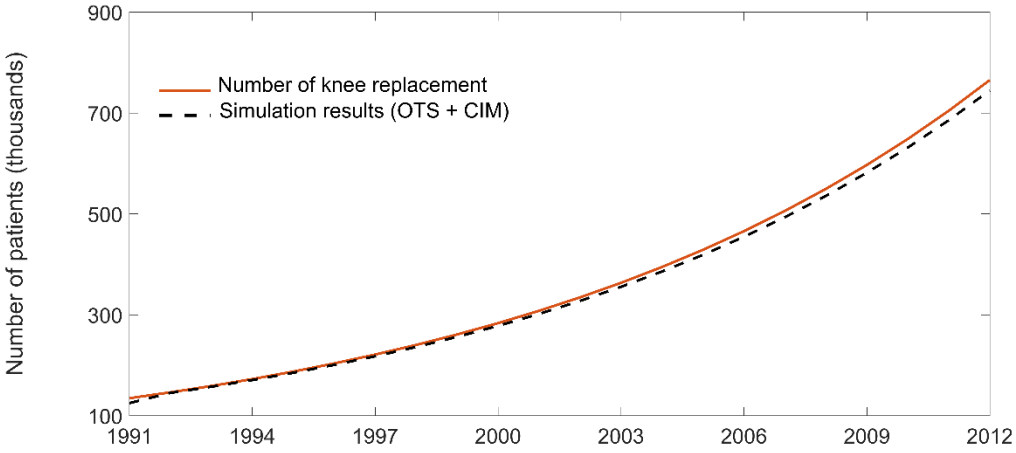
Parameters	Value	Definition
Patient-Patient contact Rate	5 /year	It is assumed each patient has contact with 5 other patients who have done knee replacement before regarding their procedure outcome each year.
Adoption Fraction of the Patients due to Awareness	0.05	Presents the fraction of the new patients willing to adopt the new product due to their contacts with other patients who are using the new products
Custom Design & Performance Improvement per Doubling of Cooperation	0.05 / year	5% improvement is assumed for doubling the CIM implants manufacturers and surgeons cooperation based on the learning curve formulation of Sterman (31, 32).
OTS Design & Performance Improvement per Doubling of Cooperation	0.025 / year	2.5% increase is assumed for doubling the cooperation of manufacturers and surgeons (31, 32). (Half the custom implants improvement rate)
Multiplication of OTS Product Cost for Custom Implants	1.25	Since the cost of Custom knee implants are very difficult to find, in the model, it is assumed that these implants cost 25% higher than OTS implants (33, 34).
Sales Reps Influence on promoting OTS (initial value)	0.7	The initial which also includes pricing arrangement between hospitals and producers of OTS implants considered as high (35).
Delay for Manufacturer to React to the Market Share to Adopt New Technology	3 years	Presents the time period takes for the implant manufacturers to switch to new technology when they see an increase in the market share of the new products.

4.3. Model Validation

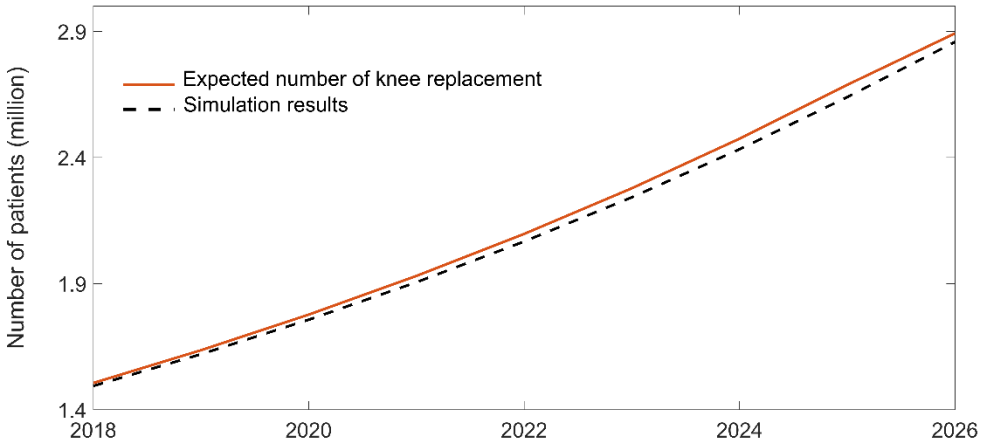
In this section, we first validate the model by replicating the historical data for OTS implant procedures. In addition to OTS procedures, to show the model robustness, we added custom implant procedures from 1990-2012 and replicated the historical data one more time under that condition. Furthermore, we used the expected number of knee replacement procedures up to 2026 (3, 36, 37) and tested the model with the estimated data to find the parts of the model that can better represent the reality and the parts that produce more error. Figure IR5 illustrates the simulation results in comparison with historical and expected future data.



a) Availability of OTS only and comparison between incoming patients and simulated outgoing patients



b) Availability of OTS and CIM and comparison between incoming patients and simulated outgoing patients



c) Availability of OTS and CIM and comparison between expected number of incoming patients and simulated outgoing patients

Figure IR5: a) Comparing historical data and simulation results from 1990 to 2012 when the OTS procedure is the only available option for patients. **b)** Comparing historical data and simulation results from 1990 to 2012 when the OTS and CIM procedures are both available. Based on the assumption that CIM procedure was available during that time to test the model reliability. **c)** Comparing expected data and simulation results from 2018 to 2026 when the OTS and CIM procedures are both available.

Concentrating on the physics of the model, which technically is the flow of patients, helped us to replicate the data with high correlation. The simple logical inflows and outflows of the stock variables could officially validate the model.

Section 5: Online Simulator Platform

To make it easier for users to run the model under different policy conditions without any software requirements, an online version of the model is developed using Forio which is accessible at: http://jalali.mit.edu/medical-tech-adoption

The interface of the online simulator is shown in Figure IR6. The online model can be simulated for periods of 1 and 3 years, or it can be simulated at once to the final time (2026). This provides the flexibility to incorporate various dynamic policies (by updating model parameters) midway through the simulation run and observe the results. The reset button returns the model to its initial conditions.

There are five parameters available to change in the online simulator:

1) Coverage of Insurance Bundled Payments for CIM: represents the coverage rate for CIM implants 0 and 90%.
2) Relative price of CIM implants to OTS: represents the magnitude of CIM implant price to OTS. The price of CIM can be changed from 0.5 to 3 times of the OTS price.
3) Percentage of performance improvement by year for either CIM or OTS implants: represents the improvement percentage in either procedure per year between 0 and 20% due to the improvement in the design phase.
4) Timesaving per procedure: represents the hours that can be saved by using CIM implant and instruments in each procedure.

The plots in the online simulator show the impacts of changing parameters above on readmission and revision surgery rates, total cost per patient, cumulative time saved for surgeons and hospitals per month, percentage of CIM adoption, and cumulative total costs for both CIM and OTS procedures.

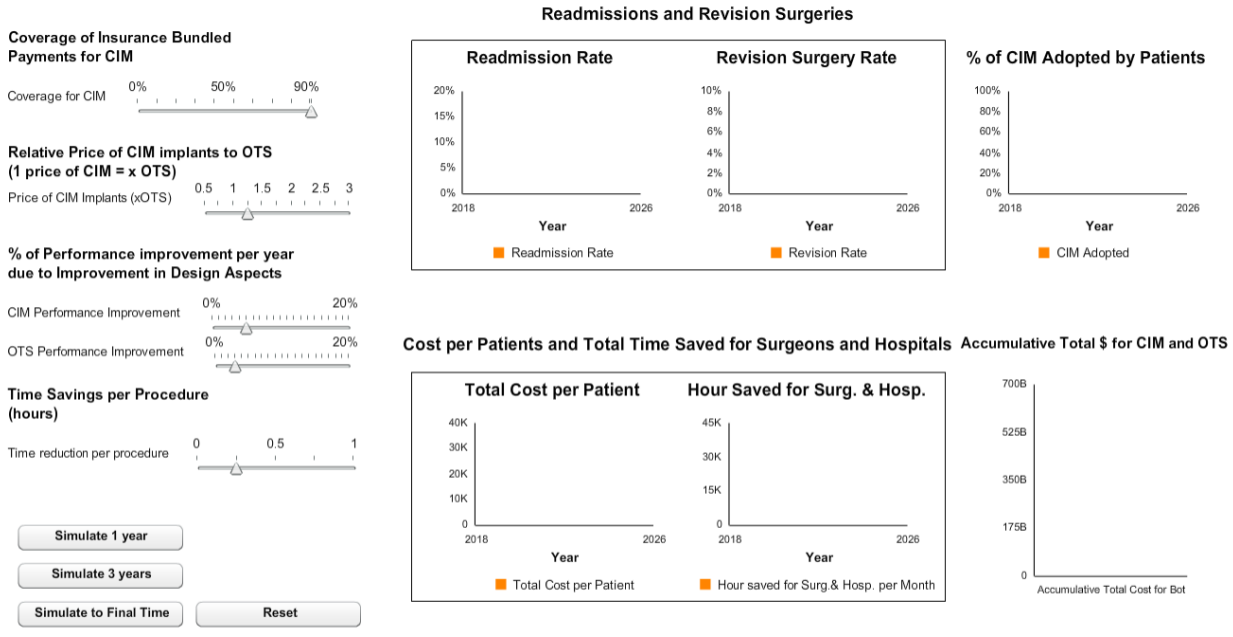


Figure IR6: Online simulator interface

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